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This report presents a number of available analytical solutions that can be used for pressure buildup calculation and three methods of performing such calculations. The methods are: manual calculation, calculation by programmable desk calculator, and calculation by digital computer. Programs for the desk calculator and for the digital computer are presented and examples of their use are given.

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FOREWORD

The Environmental Protection Agency was established to coordinate administration of the major Federal programs designed to protect the quality of our environment.

An important part of the Agency's effort involves the search for information about environmental problems, management techniques, and new technologies through which optimum use of the Nation's land and water resources can be assured and the threat pollution poses to the welfare of the American people can be minimized.

EPA's Office of Research and Development conducts this search through a nationwide network of research facilities.

As one of these facilities, the Robert S. Kerr Environmental Research Laboratory is responsible for the management of programs to: (a) investigate the nature, transport, fate, and management of pollutants in ground water; (b) develop and demonstrate methods for treating wastewaters with soil and other natural systems; (c) develop and demonstrate pollution control technologies for irrigation return flows; (d) develop and demonstrate pollution control technologies for animal production wastes; (e) develop and demonstrate technologies to prevent, control or abate pollution from the petroleum refining and petrochemical industries; and (f) develop and demonstrate technologies to manage pollution resulting from combinations of industrial wastewaters or industrial/municipal wastewaters.

This report contributes to that knowledge which is essential in order for EPA to establish and enforce pollution control standards which are reasonable, cost effective, and provide adequate environmental protection for the American public.

William C Galegar

William C. Galegar
Director

ABSTRACT

It is often necessary, in injection well design, to predict the probable rate of pressure increase in the injection reservoir that would be expected to result from a proposed injection program. Areas of application include oilfield brine injection, waterflooding for secondary oil recovery, industrial wastewater injection, uranium leaching, etc.

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SYMBOLS AND ABBREVIATIONS

a = an integer in a summation

A = area of a completely bounded reservoir, ft^2

b = an integer in a summation

B = leakage factor for semiconfined reservoirs = $\sqrt{\frac{khh_c}{k_c}}$

β = formation volume factor, RB/STB for liquid, RB/Mcf for gas

c = compressibility, psi^{-1}

C_A = shape factor for fully confined reservoirs

d = distance from top of reservoir to top of screen or perforations in a partially penetrating well, ft

ΔP_s = pressure drop across skin, psi

e = natural log base, 2.718

erf = error function

E_1 = exponential integral

f = mathematical symbol meaning "a function of"

γ_{rf} = specific weight of reservoir fluid, lb/ft^3

h = reservoir thickness, ft

h_c = thickness of semiconfining layer, ft

h_c' = thickness of second semiconfining layer, ft

h_D = dimensionless thickness = h/r_f

h_i = thickness of ith layer in a layered reservoir, ft

i = an integer in a summation

$I_o(x)$ = zero order modified Bessel function of the first kind

k = permeability, md

$\bar{k}$ = equivalent permeability of a layered reservoir, md

k_c = vertical permeability of semiconfining layer, md

k_c' = vertical permeability of second semiconfining layer, md

k_i = permeability of ith layer in a layered reservoir, md

$K_0(x)$ = zero order modified Bessel function of the second kind

k_r = radial permeability, md

k_s = permeability in the skin zone, md

k_z = vertical permeability, md

l = length of penetration of a partially penetrating well, ft

log = logarithm, base 10

ln = logarithm, base e

m = an integer in a summation

μ = viscosity, cp

μ_{if} = viscosity of injected fluid, cp

μ_{rf} = viscosity of reservoir fluid, cp

n = an integer in a summation

P_D = dimensionless pressure

P_{DF} = dimensionless pressure for a well intersected by a single vertical fracture - general case

P_{DHF} = dimensionless pressure for a well intersected by a single horizontal fracture

P_{DL} = dimensionless pressure for semiconfined reservoirs

P_{DPP} = dimensionless pressure for a partially penetrating well

P_{DWF} = dimensionless pressure for a well intersected by a single vertical fracture - wellbore case

ϕ = porosity, fraction

P_i = initial reservoir pressure, psi

P_r = reservoir pressure at radius r, psi

P_{ri} = initial reservoir pressure at radius r, ft

P_{WB} = reservoir pressure at the wellbore, psi

P_{xy} = reservoir pressure at coordinates x and y, psi

q = flow rate, STB/D for liquid, Mscf/D for gas

r = radial distance from well to point of investigation, ft

r_D = dimensionless radius = r/r_f

r_e = external radius, ft

r_f = radial extent of horizontal fracture, ft

r_{if} = radius of cylinder of injected fluid, ft

r_s = radius of skin zone, ft

r_w = radius of wellbore, ft

s = skin factor, a positive or negative number

σ = pseudo skin function for a well intersected by a single vertical fracture, dimensionless

t = time, days

t_D = dimensionless time

t_{DA} = dimensionless time based on drainage area

$(t_{DA})_{pss}$ = dimensionless time at the beginning of pseudo steady-state flow

θ = angle of dip of reservoir in the radial direction of investigation

t_{pss} = time at the beginning of pseudo steady-state flow, days

x = space coordinate, ft

x_D = dimensionless fracture coordinate = x/x_f

y = space coordinate, ft

y_D = dimensionless fracture coordinate = y/x_f

z = distance from top of reservoir to point of investigation in a reservoir with a partially penetrating well, ft

z_D = dimensionless fracture coordinate = $z_f/x_f \sqrt{k_r/k_z}$

z_f = distance from bottom of reservoir to center of horizontal fracture

ABBREVIATIONS

cp = centipoise

D = day(s)

ft = feet

md = millidarcys, 1/1000 darcy

Mscf = thousands of cubic feet of gas at standard temperature and pressure (460° R, 14.7 psi)

psi = pounds per square inch

RB = reservoir barrels, or barrels of liquid at reservoir temperature and pressure

STB = stock tank barrels, or barrels of liquid at standard temperature and pressure (520° R, 14.7 psi)

CHAPTER 1

INTRODUCTION

OBJECTIVES AND SCOPE

An engineering task that is often required of injection well operators and those regulating injection well operation is the prediction of the probable rate of pressure increase in the injection reservoir, resulting from a proposed injection operation. The pressure increase associated with any injection operation, whether it is oilfield brine injection, waterflooding for secondary oil recovery, industrial wastewater injection, uranium leaching, etc., is of concern because it is a major factor in determining the economics and the potential environmental impact of the operation on the hydrologic system.

The objective of this report is to present a number of available analytical equations that can be used for pressure buildup calculations under various hydrologic and operational conditions. Three methods of performing such calculations are presented; they are, manual calculation, calculation by use of programmable desk calculator, and calculation by digital computer. Manual calculations can be performed by anyone and are quite adequate for many simple cases, but the calculations can be tedious, if many are needed. The programmable desk calculator allows some calculations to be made that are not possible to make manually, but more importantly, it allows many calculations to be made rapidly and at little cost. The digital computer allows combinations of solutions to be made easily that can only be made with difficulty by the other methods and is the most rapid method of all, when large numbers of wells, numerous injection rates, or large numbers of calculations are involved.

In recent years, numerical models have become widely used for predicting reservoir performance. Such models are needed when reservoir properties vary considerably or where conditions exist for which analytical solutions are not available. However, for cases where analytical solutions are available, such as those given in this report, use of the analytical solution is more rapid and more accurate. Furthermore, it is good practice to check the results of a problem solved by a numerical model against the results of the analytical solution that most closely represents the problem. This helps to insure that no major error has been made in the numerical modeling process.

While none of the analytical solutions incorporated in this report are original, many of them have never been presented in a manner that would allow their use for pressure buildup (or decline) calculations without an impractical amount of effort. The writers do not know of any other existing sets of tables, programmable desk calculator programs, or FORTRAN programs that have been published that will allow the range of calculations made possible by the material in this report.

Projection of the probable pressure buildup during system design allows estimates of well numbers, well spacings, and operating rates to be made. Such projections can show whether a proposed operation is economically realistic or unrealistic. From an environmental viewpoint, the projected pressure increase is examined to determine if there is potential for hydraulic fracturing or escape of fluid through nearby abandoned wells. In many cases, the projected pressure buildup pattern is used to project the rate and direction of flow of the injected fluids in the receiving reservoir.

ORGANIZATION OF REPORT

As discussed above, three methods for pressure buildup calculation are presented, each of which is appropriate under different circumstances. Chapter 3, is devoted to the presentation of the equations that are used and to the development of examples of problem solving. The examples given in Chapter 3 are relatively simple, but are realistic problems. The examples are simple, because their solution by the manual method is demonstrated in Chapter 3. The examples are, at the same time, examples that can be used to develop competency in the operation of the programmable desk calculator and in use of the FORTRAN program.

Tables that must often be used in conjunction with the manual solution method are given in Appendix A. Programmable desk calculator programs are included in Appendix B, and a discussion of the use of the program is given in Chapter 4. The FORTRAN program is included in Appendix C and a discussion of its use is given in Chapter 5.

CHAPTER 2

THEORY OF PRESSURE BUILDUP

As discussed in the introduction, the purpose of the equations that are presented is to allow the calculation of the increase in pressure, with time, at any selected point in the vicinity of a well into which fluids are being injected. The basic equation governing steady fluid flow through an aquifer is the Darcy equation. Combination of the Darcy equation with the continuity equation and an equation of state allows development of solutions for cases in which pressure increases with time (unsteady or transient conditions).

The basic differential equation for the unsteady radial flow of a slightly compressible fluid from an injection well (or to a pumping well) is (Matthews and Russell, 1967):

$$\frac{\partial^2 P}{\partial r^2} + \frac{1}{r}\frac{\partial P}{\partial r} = \frac{\phi \mu c}{k}\frac{\partial P}{\partial t} \qquad (1)$$

In the development of Equation 1, the following assumptions were made:

1. horizontal flow
2. negligible gravity effects
3. a homogeneous and isotropic reservoir
4. a single fluid of small and constant compressibility

The equations that will be presented and analyzed in the rest of the manual are solutions of Equation 1, or a similar equation, for various selected conditions.

When a particular solution to Equation 1 or a similar equation is obtained, it is initially in a nonunitized form. That is, any set of consistent units can be used. However, an engineer or scientist will usually be working with practical units such as gallons or barrels for volume, darcys for permeability, feet for length, etc. Therefore, it is necessary to adjust the equations for these heterogeneous units by using constants. All of the equations given in this manual will be adjusted for use with the following units:

Parameter or Variable	Symbol	Practical Units
compressibility	c	psi^{-1}
porosity	ϕ	decimal fraction
reservoir thickness	h	ft
permeability	k	md
viscosity	μ	cp
pressure	P	psi
flow rate	q	STB/D
radial distance	r	ft
time	t	D

The equations can easily be converted to other practical units, if so desired.

Throughout the text, pressure buildup equations are written using dimensionless pressure (P_D) and dimensionless time (t_D). These dimensionless quantities are groups of variables that commonly occur in buildup equations and which can conveniently be replaced by a single term. Dimensionless time, for the units listed above is:

$$t_D = \frac{6.33 \times 10^{-3}\ kt}{\phi \mu c r^2} \tag{2}$$

In unsteady state or transient flow equations, dimensionless pressure (P_D) is a function of dimensionless time and, perhaps, other quantities, depending on the particular buildup solution. It is defined for each equation in which it is used, throughout the report.

The equations presented all contain the variable β, the formation volume factor, which is the ratio of the volume of the fluid being injected at reservoir pressure compared with the volume at standard conditions (520°R, 14.7 psi). For liquids, β can, for practical purposed, be considered to be 1.0, as in all examples in this report. However, β is quite variable when the injected fluid is gas. When a highly compressible fluid is being injected, β should be evaluated at an average reservoir pressure. In cases where the pressure is not known, enter a value of β = 1.0, obtain the approximate pressure, then evaluate β(Amyx, et al, 1960) and recalculate the pressure.

CHAPTER 3

PRESSURE BUILDUP EQUATIONS AND SAMPLE CALCULATIONS

This chapter is devoted to the documentation of the equations that have been selected for incorporation in the manual. Each equation is listed, the assumptions that apply are given, and an example calculation is presented. Where possible, hand solution methods are used in presenting the examples. Any example that is given can also be solved with the programmable desk calculator programs that are given and/or with a digital computer, using the FORTRAN program that is given. The desk calculator programs allow a wider range of solutions than are practical by hand and the FORTRAN program includes capabilities greater than those of the desk calculator programs.

INFINITE CONFINED RESERVOIRS

For many practical situations, an adequate approximation of the pressure buildup resulting from well injection can be obtained by assuming that:

1. The receiving reservoir is infinite in areal extent and is completely confined above and below by impermeable beds.

2. Prior to injection the piezometric surface in the vicinity of the well is horizontal, or nearly so.

3. The volume of fluid in the well is small enough so that the effect of the wellbore can be neglected.

4. The injected fluid is taken into storage instantaneously. That is, pressure effects are transmitted instantaneously through the aquifer.

To these assumptions must be added those previously listed, which are:

5. Flow is horizontal.

6. Gravity effects are negligible.

7. The reservoir is homogeneous and isotropic.

8. The injected and reservoir fluids have a small and constant compressibility.

These eight assumptions are basic to all equations in this chapter, with modifications noted where appropriate.

Constant Injection Rate

Single Well--

The equation for pressure buildup resulting from a constant rate of injection through a single well that fully penetrates the receiving aquifer (Figure 1) is (Matthews and Russell, 1967):

$$P_r = P_i + 70.6 \frac{q\mu\beta}{kh} \left[E_1 \left(\frac{39.5\ \phi\mu c r^2}{kt}\right)\right] \tag{3}$$

For cases where the quantity in parentheses ($1/t_d$) is less than 0.01, an adequate approximation of Equation 3 is (Matthews and Russell, 1967):

$$P_r = P_i + 162.6 \frac{q\mu\beta}{kh} \log \left(\frac{kt}{70.4\ \phi\mu c r^2}\right) \tag{4}$$

As an example of the use of Equations 3 and 4 assume the following conditions:

P_i = 0 psi

q = 1714 STB/D

β = 1

c = $7.5\text{x}10^{-6}$ psi $^{-1}$

k = 50 md

h = 45 ft

ϕ = 0.15

μ = 1 cp

r = .292 ft (7 inch wellbore)

t = 3650 days

Entering these values into Equation 3, the results are:

$$P_r = 0 + 53.78\ [E_1(2.08\text{x}10^{-11})]$$

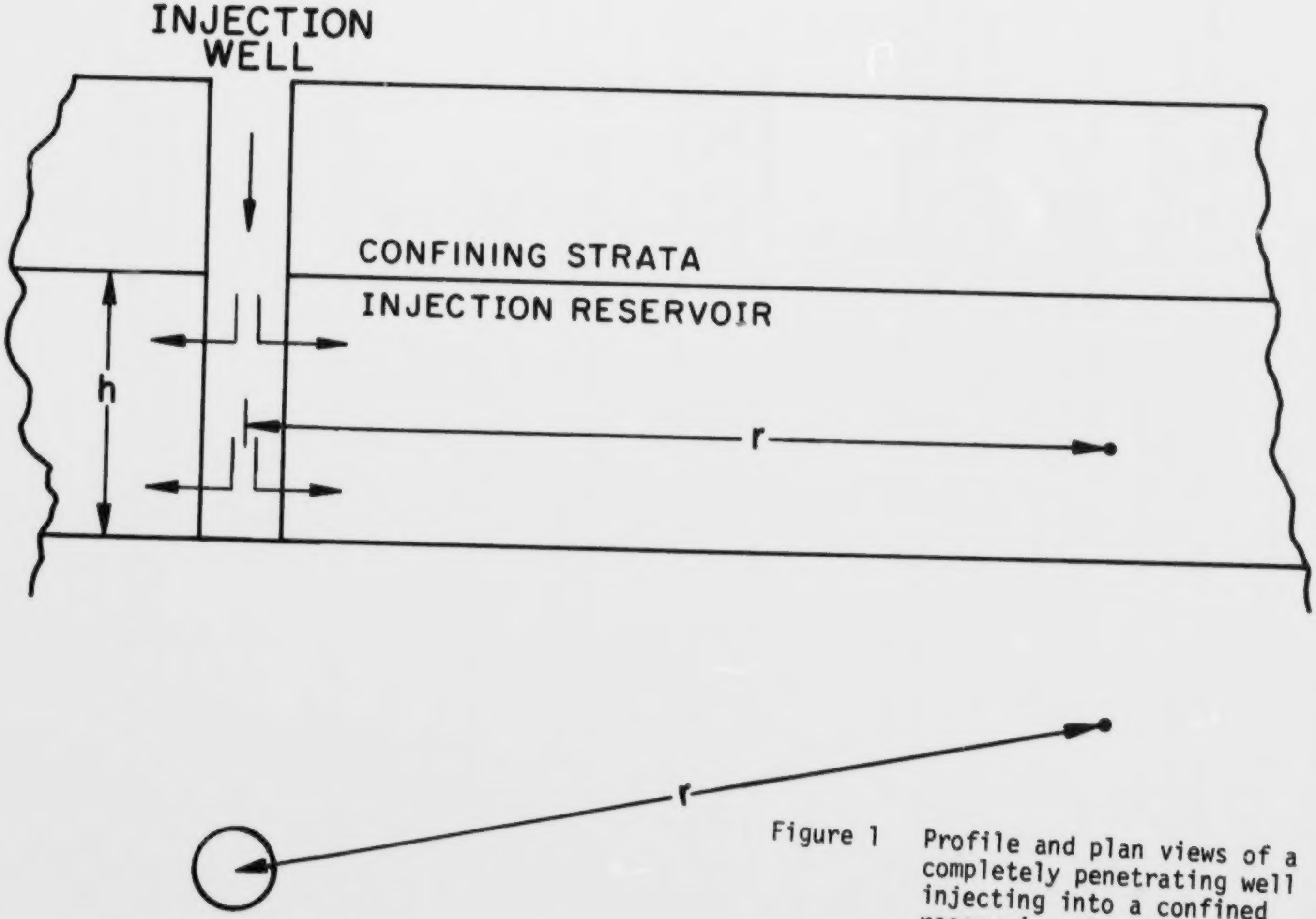

INJECTION WELL
CONFINING STRATA
INJECTION RESERVOIR
h
r
r

Figure 1 Profile and plan views of a completely penetrating well injecting into a confined reservoir. Pressure is to be calculated at a point r distance from the well.

Obtaining the E_1 value from Table A-1,

$$P_r = 0 + 53.78\ (24.02) = 1292 \text{ psi}$$

Applying Equation 4,

$$P_r = 0 + 123.9\ (10.43) = 1292 \text{ psi}$$

The two methods give the same result in this case and will give the same or nearly the same result in all cases where $1/t_d < 0.01$. Where $1/t_d > 0.01$, Equation 3 should be used to assure accurate results.

As a second example, assume all of the same conditions, but let $r = 1000$ ft. Using Equation 4, the pressure buildup is 416 psi. Equation 4 is sufficiently accurate, since $1/t_d = 2.43\text{x}10^{-4} < 0.01$.

An initial pressure of zero has been used to facilitate comparison among the various cases that are examined. In fact, the initial pressure in any subsurface reservoir cannot be zero, but rather will generally be close to the hydrostatic pressure resulting from the saturated thickness of overlying rock.

Multiple Wells--

A fortunate characteristic of the equations used in this manual is that the effects of individual wells can be superimposed to obtain the combined effect of multiple wells. That is, the pressure at any selected point in a reservoir can be evaluated by summing the pressures caused by each of the individual injection wells (Figure 4).

The equation for pressure buildup resulting from constant rate injection through multiple fully-penetrating wells is:

$$P_r = P_i + 70.6 \left[\sum_{n=1}^{m} \frac{q_n \mu_n \beta_n}{k_n h_n} \; E_1 \left(\frac{39.5\ \phi_n \mu_n c_n r_n^2}{k_n t_n} \right) \right] \qquad (5)$$

Where n is the well number.

For cases where $1/t_d < 0.01$, an adequate approximation is:

$$P_r = P_i + 162.6 \left[\sum_{n=1}^{m} \frac{q_n \mu_n \beta_n}{k_n h_n} \; \log \left(\frac{k_n t_n}{70.4\ \phi_n \mu_n c_n r_n^2} \right) \right] \qquad (6)$$

Equations 5 and 6 are the same, respectively, as Equations 3 and 4, with the additional instruction to compute the pressure for m wells and sum the pressures to obtain the total pressure at a point, which is r_n distance from well n.

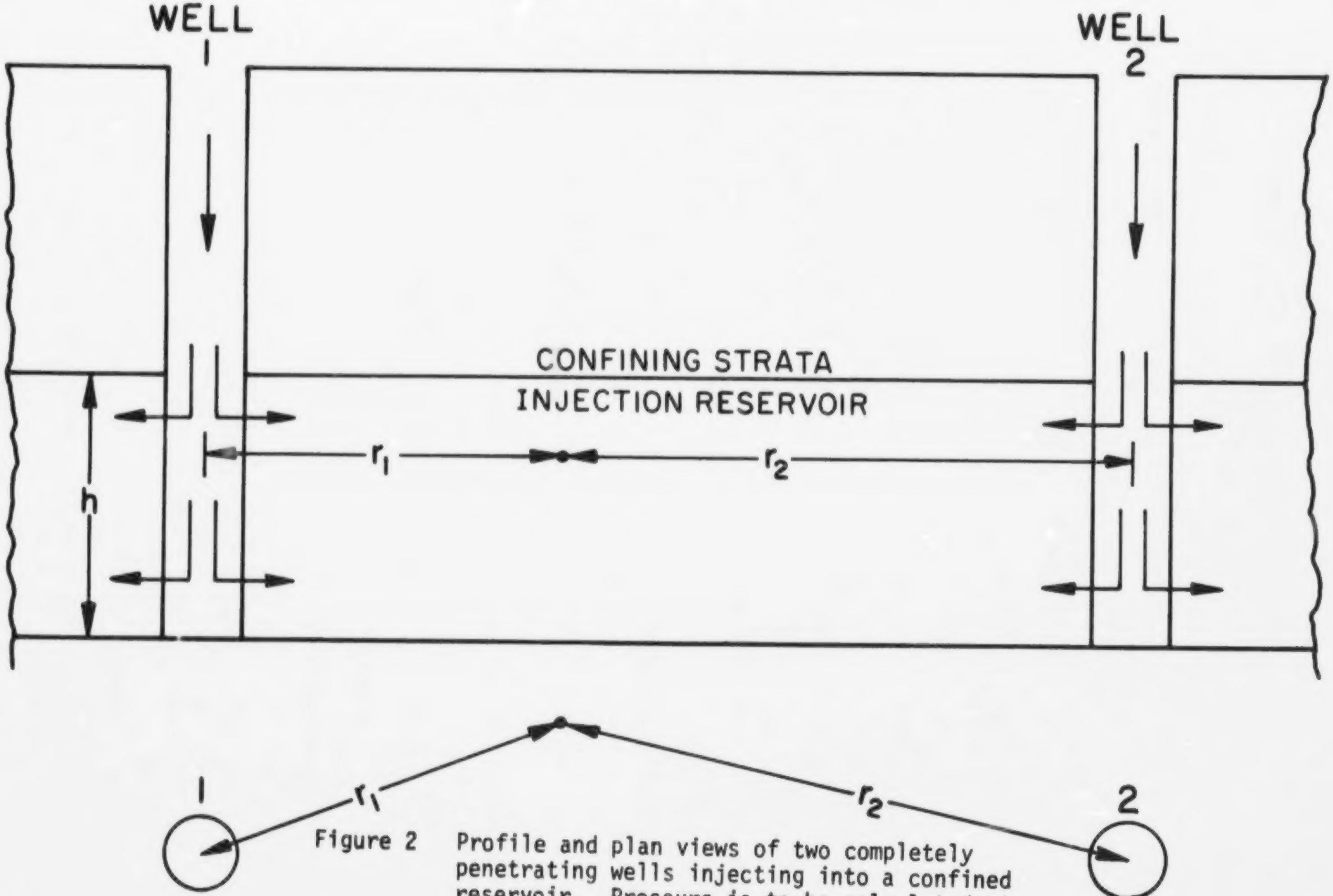

WELL 1
WELL 2
CONFINING STRATA
INJECTION RESERVOIR
r_1
r_2
h
1
2
r_1
r_2

Figure 2 Profile and plan views of two completely penetrating wells injecting into a confined reservoir. Pressure is to be calculated at a point at radii r_1 and r_2 from wells 1 and 2, respectively.

As an example of the use of Equations 5 and 6, assume the following conditions:

		Well 1	Well 2
P_i	=	0	0
q	=	100 STB/D	200 STB/D
β	=	1	1
c	=	7.5×10^{-6} psi^{-1}	7.5×10^{-6} psi^{-1}
k	=	50 md	50 md
h	=	45 ft	45 ft
ϕ	=	0.10	0.10
μ	=	1 cp	1 cp
r	=	30 ft	70 ft
t	=	100 days	150 days (begins 50 days before Well 1)

Entering these values into Equation 5, the results are

$$P_r = 0 + [3.138\ E_1(5.332\ 10^{-6})] + [6.275\ E_1(1.936 \times 10^{-5})]$$

Obtaining the values for E_1 from Table A-1,

$$P_r = 0 + [3.138\ (11.56)] + [6.275\ (10.27)] = 0 + 36.27 +$$
$$+ 64.48 = 100.8 \text{ psi}$$

Applying Equation 6,

$$P_r = 0 + [7.227 \log (1.052 \times 10^5)] + [14.45 \log (2.899 \times 10^4)]$$

$$P_r = 0 + [7.227\ (5.022)] + [14.45\ (4.462)] = 0 + 36.29 +$$
$$+ 64.48 = 100.8 \text{ psi}$$

As for the single-well example, the two equations give the same result, since $1/t_D$ is < 0.01 for both wells.

Variable Injection Rate

Single Well--

The assumptions for this case are the same as those previously applied in this chapter, except that injection is at a variable rate. The applicable equation is:

$$P_r = P_i + 70.6 \left[\sum_{a=1}^{n} \frac{(q_a - q_{a-1})\mu\beta}{kh} E_1 \left(\frac{39.5\ \phi\mu c r^2}{k(t-t_{a-1})} \right) \right] \qquad (7)$$

For cases where $1/t_d < 0.01$,

$$P_r = P_i + 162.6 \left[\sum_{a=1}^{n} \frac{(q_a - q_{a-1})\mu\beta}{kh} \log \left(\frac{k(t-t_{a-1})}{70.4\ \phi\mu c r^2} \right) \right] \qquad (8)$$

Where a is the time interval under consideration and q_a is the rate during that time interval.

The equations are based on the principle of superposition. That is, the pressure effects begin with the initial injection period t_1 and rate q_1 When a new rate q_2 is adopted, it is as if a new well begins to operate at that rate, with the effects superimposed on the original well, while the original well continues to operate at rate q_1. For example, assume that a well begins to operate at an injection rate of 200 B/D and continues at that rate for 30 days; the injection rate is then reduced to 150 B/D and continues at that rate for an additional 30 days, at which time the rate is increased to 400 B/D and continued at that rate for 10 days. This performance is shown diagrammatically in Figure 5. The problem is calculation of the pressure buildup at the well at the end of the 70 day period.

Equation 7 expanded to show the example described above and for the following values is:

$P_i = 0$

$q_1 = 200$ B/D, $q_2 = 150$ B/D, $q_3 = 400$ B/D

$\beta = 1$

$c = 7.5\text{x}10^{-6}$

$k = 50$ md

$h = 50$ ft

$\phi = .15$

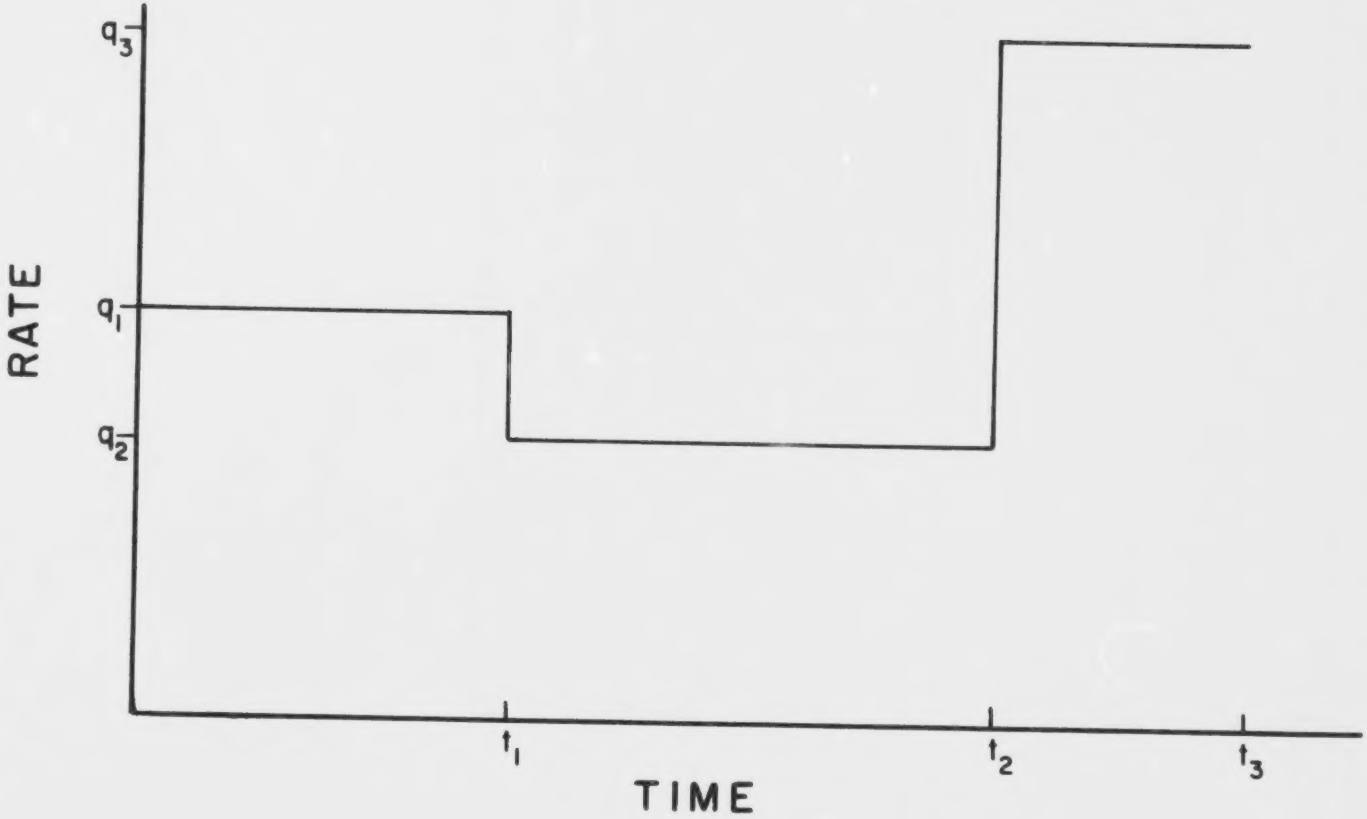


Figure 3 Diagrammatic representation of the injection history of an injection well operating at a variable rate.

μ = 1 cp

r = .292 ft (well radius)

t_1 = 30 days, t_2 = 30 days, t_3 = 10 days, t = 70 days

$$P_r = 0 + 70.6 \left[\frac{200x1x1}{50x50} E_1 \left(\frac{39.5x0.15x1x7.5x10^{-6}x(0.292)^2}{50(70-0)}\right) + \right.$$

$$+ \frac{(150-200)x1x1}{50x50} E_1 \left(\frac{39.5x0.15x1x7.5x10^{-6}x(0.292)^2}{50(70-30)}\right) +$$

$$\left. + \frac{(400-150)x1x1}{50x50} E_1 \left(\frac{39.5x0.15x1x7.5x10^{-6}x(0.292)^2}{50(70-60)}\right) \right]$$

$$P_r = 0 + 70.6 [0.08\ E_1\ (1.49x10^{-7}) - 0.02\ E_1(2.61x10^{-7}) +$$

$$+ 0.10\ E_1(1.043x10^{-6})]$$

Obtaining the E_1 values from Table A-1

$$P_r = 0 + 70.6 [0.08(20.07) - 0.02(19.50) + 0.1(18.11)]$$

$$P_r = 214 \text{ psi}$$

Applying Equation 8,

$$P_r = 0 + 162.6 [0.08 \log (6.714x10^6) - 0.02 \log (3.836x10^6) +$$

$$+ 0.1 \log (9.591x10^5)]$$

$$P_r = 0 + 162.6 [0.08(6.826) - 0.02(6.584) + 0.1(5.982)]$$

$$P_r = 214 \text{ psi}$$

Multiple Wells--

In computing the pressure buildup caused by multiple injection wells operating at variable rates, the principle of superposition is applied twice, once for computation of the pressure effects of each well and a second time in summing the effects of the individual wells. Figure 4 depicts two wells whose effects must be summed and Figure 5 shows a possible pattern of variable rate injection that might exist.

The applicable equation is:

$$P_r = P_i + \left[\sum_{b=1}^{m} \sum_{a=1}^{n} \frac{70.6(q_{ba}-q_{b(a-1)})}{k_b h_b} E_1 \left(\frac{39.5\phi_b \mu_b c_b r_b^2}{k_b(t_b - t_{b(a-1)})} \right) \right] \qquad (9)$$

Where b is the well number, a is the time interval under consideration for well b, and q_{ba} is the rate for well b during time interval a. For cases where $1/t_d < 0.01$, an adequate approximation is:

$$P_r = P_i + \left[\sum_{b=1}^{m} \sum_{a=1}^{n} \frac{162.6(q_{ba}-q_{b(a-1)})}{k_b h_b} \log \left(\frac{k_b(t_b - t_{b(a-1)})}{70.4\phi_b \mu_b c_b r_b^2} \right) \right] \qquad (10)$$

In summary, these two equations state, perform the calculation for each well, as done for the single-well variable-rate case, then sum the effects of the wells as shown for the constant rate, multiple-well example. Because examples of both of these procedures have been given, no new example will be developed for this case.

Wells With Skin Effects

Injection wells may suffer permeability loss in the vicinity of the wellbore during construction or operation or they may experience permeability gain. Permeability loss can result from drilling mud invasion, clay-mineral reactions, chemical reactions between injected and aquifer water, bacterial growth, etc. Permeability gain can result from chemical treatment such as acidization or from hydraulic fracturing and other mechanical stimulation methods. These permeability changes, which occur in the immediate vicinity of the wellbore are called "skin effects" by the petroleum industry and are described by a "skin factor" (van Everdingen, 1953; Hurst, 1953). The skin factor (s) is positive for permeability loss and negative for permeability gain.

The skin factor can vary from about -5 for a hydraulically fractured well to +∞ for a well that is completely plugged (Earlougher, 1977). The incremental pressure difference caused by the skin effect is described by:

$$\Delta P_s = s \left(\frac{q\mu}{2\pi kh} \right) \qquad (11)$$

Equation 11 is applied by combining it with equations that are derived for pressure buildup without skin effects. For example, Equation 3 is rewritten below to include skin effects:

$$P_r = P_i + \frac{70.6 q\mu\beta}{kh} \left[E_1 \left(\frac{39.5\phi\mu c r^2}{kt} \right) + 2s \right] \qquad (12)$$

When $1/t_d < 0.01$, an adequate approximation of Equation 12 is:

$$P_r = P_i + 70.6 \frac{q\mu\beta}{kh} \left[\ln \left(\frac{kt}{70.4\phi\mu c r^2}\right) + 2s\right] \tag{13}$$

Equations 12 and 13 are only valid at the wellbore. No equations are presented here for calculation of pressure buildup near the wellbore, in the zone of damage or improvement, because this zone is relatively thin and because the calculations are of relatively limited application. Outside of the skin zone, the standard equations can be applied with no correction (Earlougher, 1977). The thickness of the skin is determined by(Hawkins, 1956):

$$r_s = r_w e^{s\, k_s/k-k_s} \tag{14}$$

Seldom, if ever, will k_s be known. Reasonable estimates of k_s can, however, be made to allow calculation of the range of possible skin thicknesses. Consideration of the sources of permeability reduction around a wellbore indicates that, in the case of wellbore damage, r_s would seldom be greater than a few feet. The radius of permeability improvement can be greater, in the tens of feet for an ordinary hydraulic fracturing program, but probably less than 100 feet unless massive fracturing is done. It would, therefore, be safe to use 100 feet as the maximum r_s, except in cases of massive hydraulic fracturing.

As an example of the significance of the skin factor, the example that accompanies Equation 4 has been recomputed below for s=2 (wellbore damage) and s=-2 (wellbore improvement), using Equation 13.

For the wellbore damage case, where s=2,

$$P_r = 0 + 53.78\ [24.02 + 2(2)]$$

$$P_r = 1507 \text{ psi}$$

For the wellbore improvement case, where s=-2,

$$P_r = 0 + 53.78\ [24.02 + 2(-2)]$$

$$P_r = 1077 \text{ psi}$$

These values compare with P_r = 1292 psi for the wellbore with no skin effect.

It should be noted that these examples are computed for pressure buildup at the well. As discussed above, s is assumed to be zero and the ordinary buildup equations applied for points outside of the skin zone, which is estimated by Equation 14 or assumed to be less than 100 feet, if Equation 14 can not be used.

Partially Penetrating or Partially Completed Wells

It is generally assumed, in estimating the pressure effects of injection wells, that the wells will be drilled completely through the injection reservoir. This will usually be true, since it maximizes the injection efficiency of the well. However, for mechanical or geological reasons, drilling is sometimes stopped before complete penetration of the reservoir has been achieved. Such wells are described as partially penetrating. In other cases, a well may be drilled completely through a reservoir, but only a part of the reservoir is completed for injection. Figure 6 depicts partially penetrating and partially completed wells. The equation for pressure buildup as a result of injection into (pumping from) such a well (Hantush, 1964; Witherspoon, et al, 1967) is:

$$P_r = P_i + P_{DPP}\left(\frac{141.2q\mu\beta}{\phi\mu c r^2}\right) \tag{15}$$

where:

$$P_{DPP} = \frac{1}{2}\left[E_1\left(\frac{1}{4t_D}\right) + f(r, h, l, d, z)\right] \tag{16}$$

Partial penetration results in greater pressure buildup (decline) at and near the wellbore than would be experienced in a fully penetrating well for the same injection (pumping) rate. The magnitude of difference depends on the degree of penetration, l; the ratio of the radius of investigation to aquifer thickness, r/h; the length of the completed interval, l-d; and the vertical point of investigation, z. The expanded form of Equation 15 is too complex for practical use by hand and the number of variables so large that it is impractical to provide tables for evaluation of P_{DPP}. Therefore, solutions of Equation 15 are provided. through programs for the programmable desk calculator and for digital computers using FORTRAN.

As an example of the effect of partial penetration on pressure buildup, consider the example given for a single fully penetrating well injecting at a constant rate, except that the well will now penetrate only 10 feet into the injection reservoir. The example data are:

P_i = 0 psi

q = 1714 STB/D

β = 1

c = 7.5×10^{-6} psi^{-1}

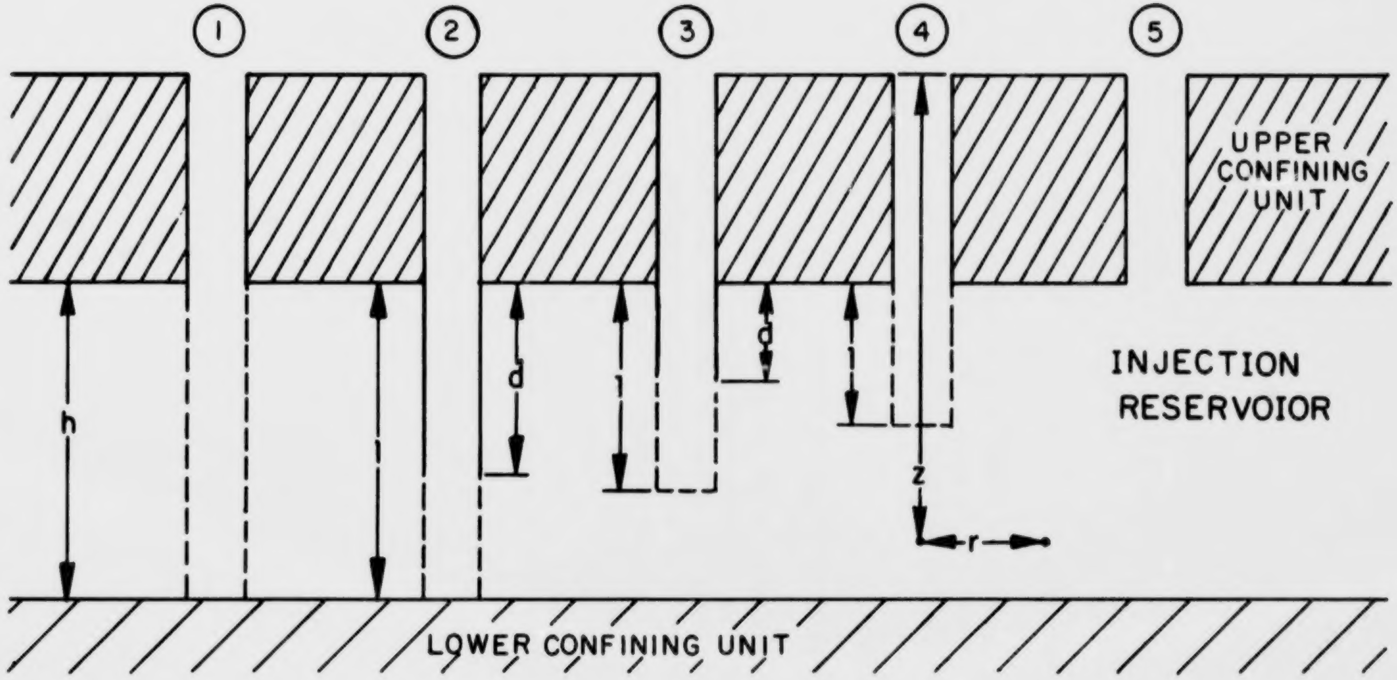

1
2
3
4
5
UPPER CONFINING UNIT
h
d
l
d
l
z
r
INJECTION RESERVOIR
LOWER CONFINING UNIT

Figure 4 Wells with varying degrees of penetration and completion

1. Fully penetrating fully completed well.
2. Fully penetrating partially completed well.
3. Partially penetrating partially completed well.
4. Partially penetrating fully completed well.
5. Non-penetrating well.

k = 50 md

h = 45 ft

ϕ = 0.15

μ = 1 cp

r = .292 ft

l = 10 ft

d = 0 ft

z = 0 ft

t = 3650 days

The pressure buildup is 2704 psi, which compares with the value of 1292 psi for the fully penetrating well. The vertical point (z=0) selected for evaluation yields the maximum pressure buildup.

Fractured Reservoirs

Single Vertical Fracture--Wellbore Case--

It is a common practice to artificially fracture injection wells, by hydraulic means, to increase their capacity to accept injected fluid. Such fracturing will affect pressure buildup, particularly near the well. Although the geometry of induced hydraulic fractures is never exactly known, estimates of fracture length can be obtained by well testing. Under the conditions that most commonly exist, induced hydraulic fractures are vertical (Hubbert and Willis, 1957). For a well that completely penetrates an infinite confined aquifer that is intersected by a single vertical fracture, the equation for pressure buildup at the well is (Gringarten et al, 1974):

$$P_{WB} = P_i + P_{DWF} \left(\frac{141.2 q \mu \beta}{kh} \right) \tag{17}$$

Where:

$$P_{DWF} = \sqrt{\pi t_D}\ \mathrm{erf} \left(\frac{1}{2\sqrt{t_D}} \right) + \frac{1}{2} E_1 \left(\frac{1}{4t_D} \right) \tag{18}$$

and,

$$t_D = \frac{6.33 \times 10^{-3} kt}{\phi \mu c x_f^2} \tag{19}$$

Equation 17 is for a fracture across which flow is uniform. Alternative solutions are available that consider the fracture to be of infinite conductivity, but the uniform flow solution is considered to be more realistic (Earlougher, 1977).

As an example of the use of Equation 17, assume:

$P_i = 0$ psi

$q = 1714$ bbl/day

$\beta = 1$

$c = 7.5\text{x}10^{-6}\text{psi}^{-1}$

$k = 50$ md

$h = 45$ ft

$\phi = 0.15$

$\mu = 1$ cp

$x_f = 10$ ft

$t = 3650$ days

From Equation 19,

$$t_D = \frac{(6.33\text{x}10^{-3})(50)(3650)}{(0.15)(1)(7.5\text{x}10^{-6})(10)^2} = 1.027\text{x}10^7$$

From Equation 18,

$$P_{DWF} = 5680 \text{ erf}(1.56\text{x}10^{-4}) + \frac{1}{2} E_1(2.435\text{x}10^{-8})$$

Using Tables A-1 and A-2,

$$P_{DWF} = 5680\ (1.8\text{x}10^{-4}) + \frac{1}{2}\ (16.95) = 9.5$$

Then from Equation 17,

$$P_{WB} = 0 + 9.5 \left(\frac{141.2\text{x}1714\text{x}1\text{x}1}{50\text{x}45}\right) = 1021 \text{ psi}$$

Single Vertical Fracture--General Case--

The previous equations apply only at the wellbore. A general solution that can be used for points other than the wellbore is (Gringarten, et al, 1974):

$$P_{xy} = P_i + P_{DF}\left(\frac{141.2q\mu\beta}{kh}\right) \tag{20}$$

Where:

$$P_{DF} = \frac{1}{2}(\ln t_D + 2.809) + \sigma(x_D, y_D) \tag{21}$$

and

$$t_D = \frac{6.33\mathrm{x}10^{-3}kt}{\phi\mu c(x_f)^2},\ x_D = \frac{x}{x_f},\ y_D = \frac{y}{x_f}$$

As an example, use all of the data for the previous fracture case, except let the fracture be 100 feet in radial length and consider a point at 50 feet from the wellbore and 50 feet outside of the fracture plane. From Equation 21,

$$P_{DF} = \frac{1}{2}\left(\ln \frac{(6.33\mathrm{x}10^{-3})(50)(3650)}{(0.15)(1)(7.5\mathrm{x}10^{-6})(100)^2} + 2.809\right) +$$

$$+ \sigma(x_D = 0.5,\ y_D = 0.5)$$

From Table A-3, $\sigma = -0.257$

and

$$P_{DF} = \frac{1}{2}(11.54 + 2.809) - 0.257 = 6.92$$

Therefore, from Equation 20

$$P_{xy} = 0 + 6.92\left(\frac{141.2\mathrm{x}1714\mathrm{x}1\mathrm{x}1}{50\mathrm{x}45}\right) = 744 \text{ psi}$$

Single Horizontal Fracture--

In areas where the sedimentary rock sequence is under active tectonic compression, hydraulic fractures would be expected to be horizontal (Hubbert and Willis, 1957). Although this situation is relatively uncommon, equations have been developed to simulate it. For a well penetrated by a single horizontal symmetrical fracture of radius r_f centered at the well and with all other assumptions the same as given at the beginning of the section (Gringarten and Ramey, 1974):

$$P_r = P_i + P_{DHF}\left(\frac{141.2q\mu\beta}{kh}\right) \quad (22)$$

For points of investigation (r) that are greater than

$$r > r_f + 3h$$

and for

$$t_D \geq 12.5(2r_D^2+1), \text{ and } t_D \geq \frac{5}{\pi^2} h_D^2$$

$$P_{DHF} = \frac{1}{2}[\ln (t_D/r_D^2) + 0.81] \quad (23)$$

Where:

$$t_D = \frac{6.33\text{x}10^{-3}kt}{\phi\mu c r_f^2}$$

$$h_D = h/r_f$$

$$r_D = r/r_f$$

As defined, the solution given above is limited to points which are farther from the well than $r_f + 3h$. For example, if the fracture has a radius of 100 feet and the formation is 50 feet thick, then the solution can be applied at a radial distance greater than 100 + 3(50) = 250 feet. The t_D limitations must also be met. In order to obtain solutions for points of investigation closer to the well, the programmable desk calculator or FORTRAN programs must be used. As an example of the application of Equations 22 and 23, assume the following conditions.

P_i = 0 psi

q = 5000 STB/D

μ = 1

β = 1

k = 100 md

h = 50 ft

ϕ = 0.25

c = $7.5\text{x}10^{-6}\text{psi}^{-1}$

$r_f = 100$ ft

$r = 300$ ft

$t = 1000$ days

First, checking t_D against the limitations that are given,

$$t_D = \frac{(6.33\text{x}10^{-3})(100)(1000)}{(0.25)(1)(7.5\text{x}10^{-6})(100)^2} = 3.38\text{x}10^4$$

Therefore:

$$t_D > 12.5(2r_D^2+1) > 238,$$

$$t_D > \frac{5}{\pi^2} h_D^2 > 2, \text{ and}$$

$$r > r_f + 3h > 250$$

Since the necessary conditions are met, Equations 22 and 23 can be used. From Equation 23,

$$P_{DHF} = \frac{1}{2} [\ln \left(\frac{3.38\text{x}10^4}{9}\right) + 0.81] = 4.52$$

and from Equation 22

$$P_r = 0 + 4.52\left(\frac{141.2\text{x}5000\text{x}1\text{x}1}{100\text{x}50}\right) = 640 \text{ psi}$$

INFINITE SEMICONFINED RESERVOIRS

The beds considered to provide confinement of the receiving aquifer may be sufficiently permeable so that significant pressure bleed-off may occur by virtue of vertical transfer of fluid through them. The assumptions applied in the infinite confined aquifer case apply except that:

1. The confining bed(s) is (are) sufficiently permeable so that the transfer of fluid across it (them) must be considered.
2. The adjacent aquifer(s) is (are) permeable enough so that no significant pressure buildup occurs in it (them).
3. Compressibility of the caprock(s) is neglected.

Leakage in One Direction

The equation for pressure buildup as a result of a fully penetrating well injecting into a reservoir fully confined on one side and semiconfined on the other is (Hantush and Jacob, 1955):

$$P_r = P_i + P_{DL}\left(\frac{141.2q\mu\beta}{kh}\right) \qquad (24)$$

Where:

$$P_{DL} = f(t_D, r/B)$$

$$t_D = \left(\frac{6.33\text{x}10^{-3}kt}{\phi\mu cr^2}\right)$$

$$B = \sqrt{khh_c/k_c}$$

As an example of the use of Equation 24, apply all of the same values used in the example of the fully penetrating well with a constant injection rate; that is:

$P_i = 0$

$q = 1714$ bb/day

$\beta = 1$

$c = 7.5\text{x}10^{-6}\text{psi}^{-1}$

$k = 50$ md

$h = 45$ ft

$\phi = .15$

$\mu = 1$ cp

$r = 0.292$ ft

$t = 3650$ days

Additionally:

$h_c = 100$ ft

$k_c = 1$ md

Therefore:

$$t_d = 1.2 \times 10^{10}$$

and

$$B = 474$$

$$\frac{r}{B} = 6.16 \times 10^{-4}$$

From Table A-5, $P_D = 7.50$

and

$$P_r = 7.50(107.6) = 807 \text{ psi}$$

This value compares with the value of 1292 psi for the completely confined case. Now, to test the validity of this calculation assume k_c=0.001 md and h_c=1000. For these values, the answer should approach the completely confined case. For these two new values,

$$t_D = 1.2 \times 10^{10}$$

and

$$B = 4.74 \times 10^4, \frac{r}{B} = 6.16 \times 10^{-6}$$

From Table A-5, $P_D = 11.78$ and

$$P_r = 1268 \text{ psi}$$

This answer compares well with the 1292 psi calculated for the completely confined case.

Leakage in Two Directions

The equations for determination of pressure buildup in an aquifer that is semiconfined both above and below are as given for leakage in one direction, except that:

$$B = \sqrt{\frac{khh_c h_c'}{k_c' h_c + k_c h_c'}}$$

No example is given, since the procedure is exactly as that developed for leakage in one direction.

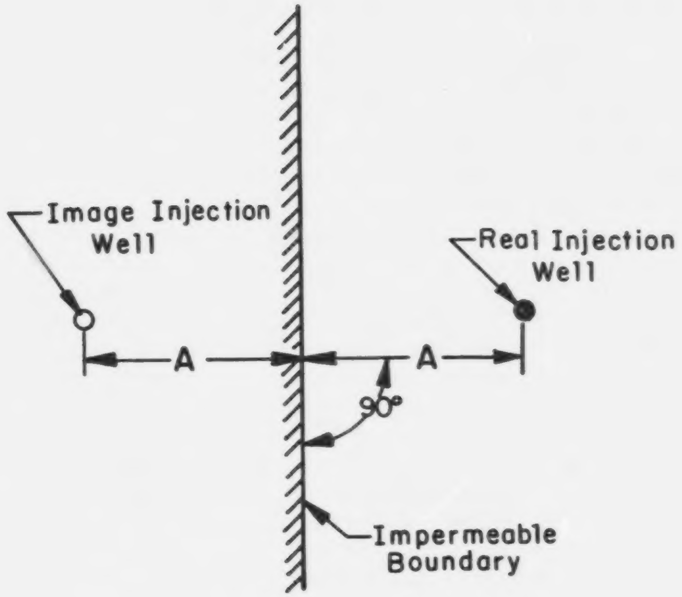


Image Injection Well
Real Injection Well
A
A
90°
Impermeable Boundary

Figure 5 Plan view of an injection well adjacent to an impermeable boundary, with an image injection well used to simulate the boundary.

BOUNDED RESERVOIRS

Linear Boundaries

In the preceeding two sections, the aquifers being injected into (pumped from) were considered to be infinite in areal extent. In many cases the injection reservoir will be bounded on one or more sides by geological features, principally faults or facies changes, that act as flow barriers or recharge sources. Such features cause the aquifers to have limited extent. The presence of flow barriers or recharge sources is handled by use of image well theory in which imaginary wells are used to hydraulically simulate the effect of the boundary (Todd, 1959; Davis and DeWiest, 1966; Walton, 1970; Earlougher, 1977).

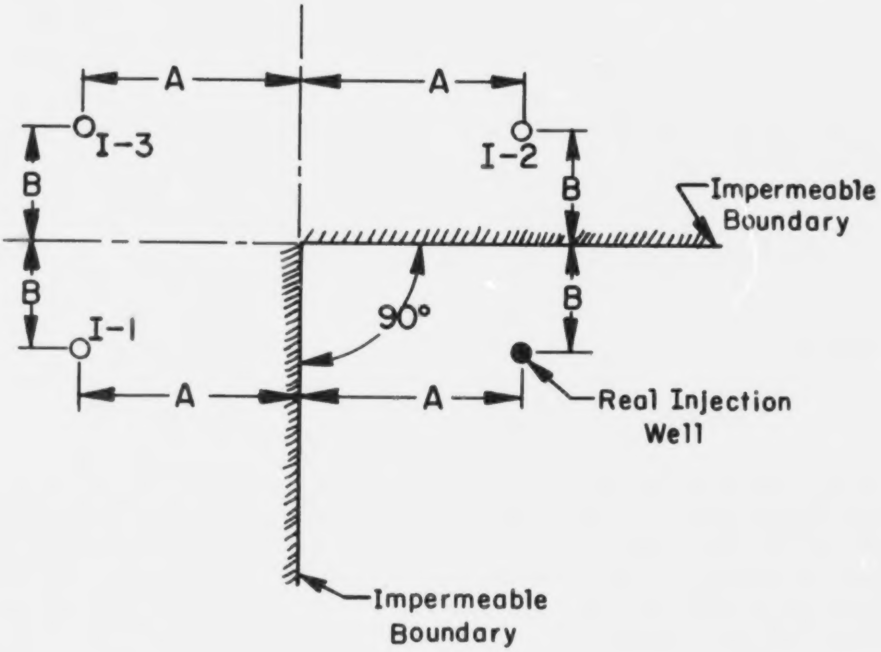
Figure 5 shows the placement of an image well to simulate an impermeable fault adjacent to a single injection well. The image well is considered to be receiving the same flow as the real well and the aquifer to have the same properties as at the real well. The pressure buildup at any point of investigation is computed by summing the effects of the real well and the image well. If the boundary were leaky, one through which flow could occur with no perceptible pressure buildup, then the image well would be a pumping well that would deplete reservoir pressure rather than add to it. Where several injection wells are present, each one will have its own image well and all real and image wells will contribute to the total reservoir pressure at any selected point of investigation. In other words, the problem is simply that of a multiple well system.

The image well concept is relatively easy to employ for a single hydrologic boundary, but becomes more complex for multiple boundaries, since multiple image wells are required for each real well. Figure 6 shows the placement of image wells in the case of a single injection well and two impermeable barriers intersecting at right angles. For a more complete discussion of image wells, including development of image well systems for boundaries intersecting at angles of less than 90° (wedge-shaped reservoirs) the reader is referred to Ferris, et al (1962).

No example is given because, as mentioned above, once the image wells have been located, the problem is handled as any multiple well problem by superimposing the effects of all real and image wells at the point of investigation.

Completely Bounded Reservoirs

During injection into (pumping from) completely bounded or closed reservoirs, a relatively short initial time period occurs during which pressure changes are nonuniform throughout the reservoir. After this initial period, as the pressure changes with time, it changes uniformly throughout the reservoir (Earlougher, 1977). During the second period of so-called pseudosteady-state pressure change, the pressure buildup (drawdown) at the well is given by (Earlougher, 1977):


A
A
I-3
I-2
B
B
Impermeable Boundary
B
B
90°
I-1
A
A
Real Injection Well
Impermeable Boundary

I-1, I-2, I-3 Are Image Injection Wells

Figure 6 Plan view of a real injection well adjacent to two intersecting impermeable boundaries with the image-well system used to simulate the boundaries.

$$P_{WB} = P_i + P_D\left(\frac{141.2q\mu\beta}{kh}\right) \tag{25}$$

Where

$$P_D = 2\pi t_{DA} + \frac{1}{2}\ln\left(\frac{A}{r_w^2}\right) + \frac{1}{2}\ln\left(\frac{2.2458}{c_A}\right) \tag{26}$$

and

$$t_{DA} = \frac{6.331\text{x}10^{-3}kt}{\phi\mu cA} \tag{27}$$

The time necessary for flow to become pseudosteady-state can be estimated from:

$$t_{pss} \geq \frac{\phi\mu cA}{6.331\text{x}10^{-3}k}(t_{DA})_{pss} \tag{28}$$

Where:

$(t_{DA})_{pss}$ is given in the "Exact for t_{DA} >" column in Table 1.

As an example of the calculation of pressure buildup in completely bounded reservoirs, assume a square reservoir created by impermeable boundaries on four sides, with the sides each 5,000 feet in length, and the well centered in the reservoir. Calculate the pressure buildup for the same data used in the single fully-penetrating well injecting into an infinite confined aquifer.

The data are:

$P_i = 0$

$q = 1714$ STB/D

$\beta = 1$

$c = 7.5\text{x}10^{-6}$

$k = 50$ md

$h = 45$ ft

$\phi = 0.15$

$\mu = 1$ cp

$r = .292$ ft

$A = 25{,}000\ \text{ft}^2$

$t = 3650$ days

First, verify that the pseudosteady-state solution applies by use of Equation 28.

$$t_{pss} \geq \frac{(0.15)(1)(7.5\text{x}10^{-6})(25{,}000)}{(6.331\text{x}10^{-3})(50)} (t_{DA})_{pss}$$

From Table 1, $(t_{DA})_{pss} = .05$, therefore:

$t_{pss} = 0.004$ days and Equation 26 can be used, since the time of interest is 3,650 days.

From Equations 26 and 27 and Table 1:

$$P_D = 2\pi(41{,}081) + \frac{1}{2}\ln\,(2.932\text{x}10^5) - 1.3106$$

$$P_D = 2.581\text{x}10^5 + 6.29 - 1.31$$

$$P_D \cong 2.581\text{x}10^5$$

From Equation 25:

$$P_{WB} = 0 + 2.581\text{x}10^5\left[\frac{(141.2)(1714\quad)(1)(1)}{(50)(45)}\right]$$

$$P_{WB} \cong 27.8\text{x}10^6\ \text{psi}$$

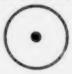
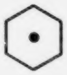
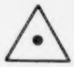
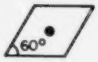
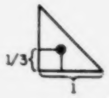
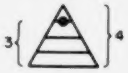
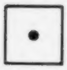
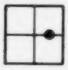
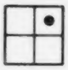
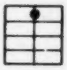
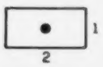
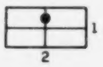
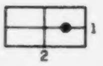
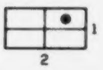
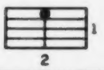
The resulting answer of $27.8\text{x}10^6$ psi is clearly unrealistic, but it emphasizes the fact that such a completely bounded reservoir is not suitable for injection use under the conditions specified.

RESERVOIRS WITH VARIABLE PERMEABILITY

Thus far, in the presentation, reservoirs have been assumed to be homogeneous and isotropic and to be characterized by a single average value of permeability. This is probably seldom close to the actual circumstances, but for reasons that will be explained this assumption

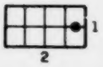
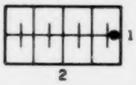
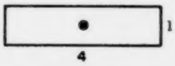
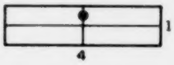
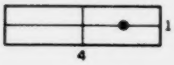
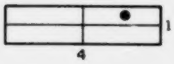
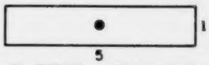
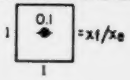
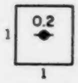
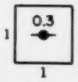
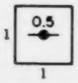
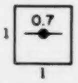
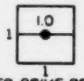
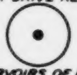
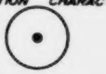
TABLE 1--SHAPE FACTORS FOR VARIOUS CLOSED SINGLE-WELL AREAS

(Earlougher, 1977)

IN BOUNDED RESERVOIRS	C_A	$\ln C_A$	$1/2 \ln\left(\frac{2.2458}{C_A}\right)$	EXACT FOR $t_{DA} >$	LESS THAN 1% ERROR FOR $t_{DA} >$	USE INFINITE SYSTEM SOLUTION WITH LESS THAN 1% ERROR FOR $t_{DA} <$
	31.62	3.4538	-1.3224	0.1	0.06	0.10
	31.6	3.4532	-1.3220	0.1	0.06	0.10
	27.6	3.3178	-1.2544	0.2	0.07	0.09
	27.1	3.2995	-1.2452	0.2	0.07	0.09
	21.9	3.0865	-1.1387	0.4	0.12	0.08
	0.098	-2.3227	+1.5659	0.9	0.60	0.015
	30.8828	3.4302	-1.3106	0.1	0.05	0.09
	12.9851	2.5638	-0.8774	0.7	0.25	0.03
	4.5132	1.5070	-0.3490	0.6	0.30	0.025
	3.3351	1.2045	-0.1977	0.7	0.25	0.01
	21.8369	3.0836	-1.1373	0.3	0.15	0.025
	10.8374	2.3830	-0.7870	0.4	0.15	0.025
	4.5141	1.5072	-0.3491	1.5	0.50	0.06
	2.0769	0.7309	+0.0391	1.7	0.50	0.02
	3.1573	1.1497	-0.1703	0.4	0.15	0.005

(continued)

TABLE 1--(continued)

	C_A	$\ln C_A$	$1/2 \ln \left(\frac{2.2458}{C_A}\right)$	EXACT FOR $t_{DA} >$	LESS THAN 1% ERROR FOR $t_{DA} >$	USE INFINITE SYSTEM SOLUTION WITH LESS THAN 1% ERROR FOR $t_{DA} <$
	0.5813	-0.5425	+0.6758	2.0	0.60	0.02
	0.1109	-2.1991	+1.5041	3.0	0.60	0.005
	5.3790	1.6825	-0.4367	0.8	0.30	0.01
	2.6896	0.9894	-0.0902	0.8	0.30	0.01
	0.2318	-1.4619	+1.1355	4.0	2.00	0.03
	0.1155	-2.1585	+1.4838	1.0	2.00	0.01
	2.3606	0.8589	-0.0249	1.0	0.40	0.025
IN VERTICALLY-FRACTURED RESERVOIRS	USE $(x_e/x_f)^2$ IN PLACE OF A/r_w^2 FOR FRACTURED SYSTEMS					
	2.6541	0.9761	-0.0835	0.175	0.08	CANNOT USE
	2.0348	0.7104	+0.0493	0.175	0.09	CANNOT USE
	1.9986	0.6924	+0.0583	0.175	0.09	CANNOT USE
	1.6620	0.5080	+0.1505	0.175	0.09	CANNOT USE
	1.3127	0.2721	+0.2685	0.175	0.09	CANNOT USE
	0.7887	-0.2374	+0.5232	0.175	0.09	CANNOT USE
IN WATER-DRIVE RESERVOIRS						
	19.1	2.95	-1.07	—	—	—
IN RESERVOIRS OF UNKNOWN PRODUCTION CHARACTER						
	25.0	3.22	-1.20	—	—	—

will often yield adequate results. In those cases where variable permeability must be considered, special techniques can be applied.

Layered Reservoirs

Most reservoirs are layered, because of stratification developed during their deposition or as a result of selective development of secondary permeability. Permeable layers may be vertically interconnected or they may be separated by thin shales, dense carbonate layers, evaporite layers or other relatively impermeable beds. Where there is hydraulic interconnection, the system is often referred to as a layered reservoir with crossflow. Where the permeable layers are hydraulically interconnected only through the wellbore, the system is layered without crossflow.

Layered Reservoirs With Crossflow--

Figure 7 shows an aquifer with three layers that are hydraulically connected. Russell and Prats (1962) concluded that such reservoirs can be treated as a single equivalent homogeneous system. The equivalent system is determined by using the relationship:

$$\bar{k} = \frac{\sum\limits_{i=1}^{n} k_i h_i}{\sum\limits_{i=1}^{n} h_i} \qquad (29)$$

For example, given the following data:

$k_1 = 50$ md　　$h_1 = 30$ ft

$k_2 = 200$ md　　$h_2 = 40$ ft

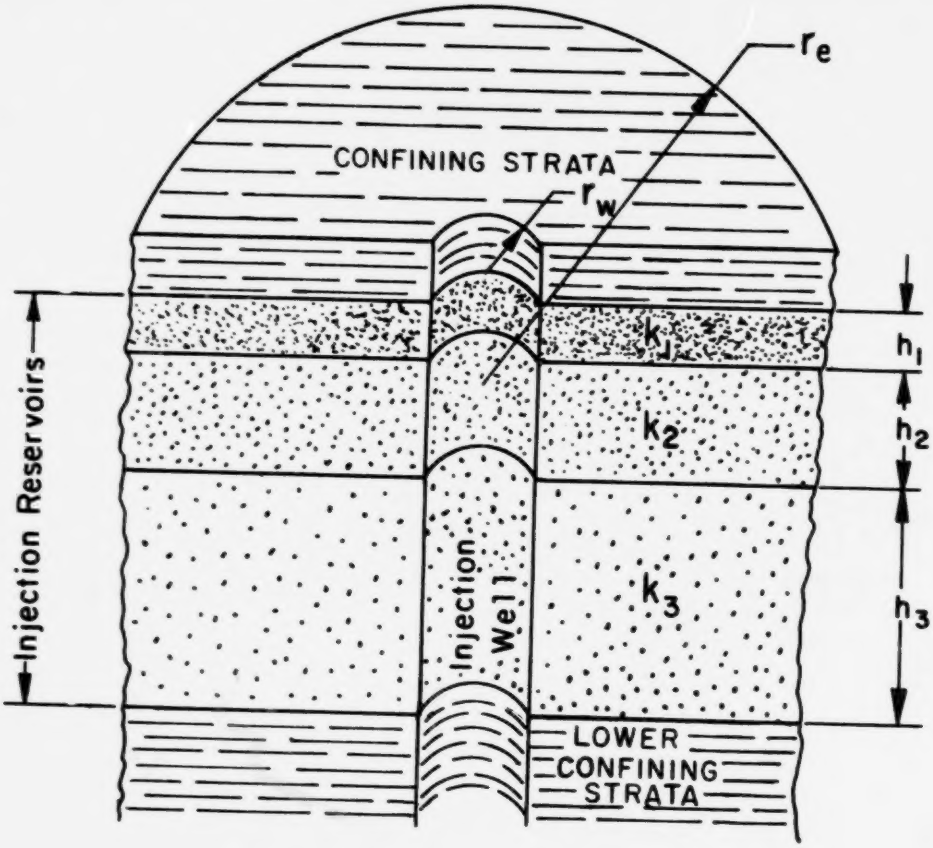
$k_3 = 75$ md　　$h_3 = 200$ ft

The equivalent reservoir permeability is:

$$\bar{k} = \frac{(50\text{x}30)+(200\text{x}40)\ (75\text{x}200)}{30+40+200} = 91 \text{ md}$$

And the equivalent reservoir thickness is 270 ft.

The equivalent $\bar{k}$ and total h are used in equations such as 3, 4, etc., just as if the aquifer were a single homogeneous unit.



r_e
CONFINING STRATA
r_w
Injection Reservoirs
k_1
h_1
k_2
h_2
k_3
h_3
Injection Well
LOWER CONFINING STRATA

Figure 7 A layered reservoir, with vertical communication between layers.

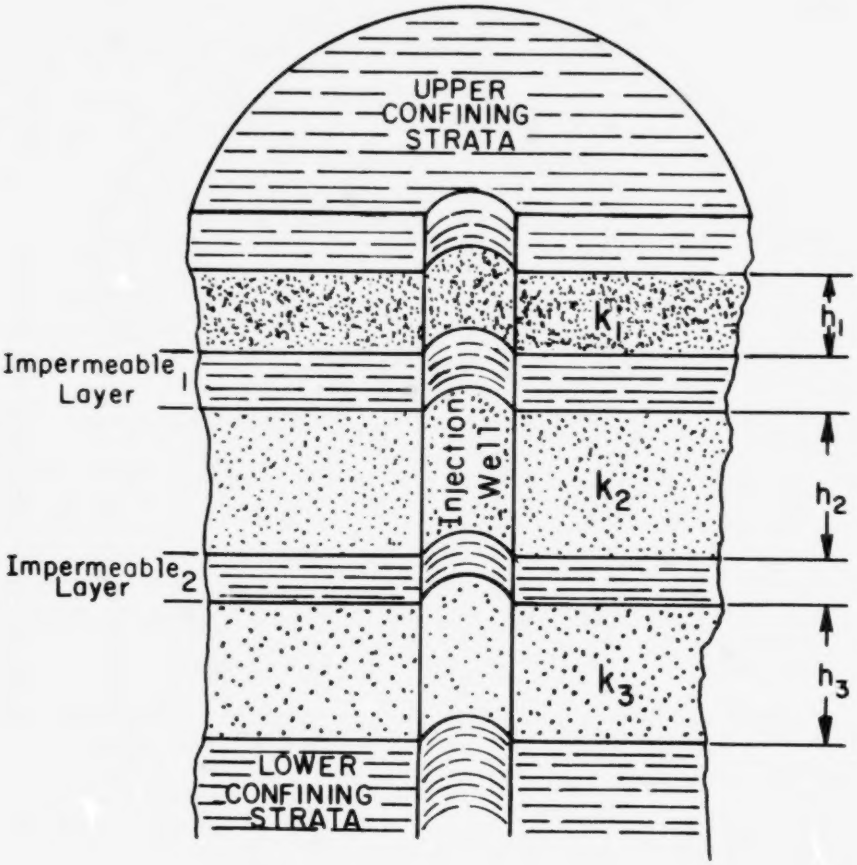

UPPER CONFINING STRATA
k_1
h_1
Impermeable Layer 1
Injection Well
k_2
h_2
Impermeable Layer 2
k_3
h_3
LOWER CONFINING STRATA

Figure 8   A layered reservoir without vertical communication between layers.

Layered Reservoirs Without Crossflow--

In aquifers where the permeable layers are separated by impermeable ones, as shown in Figure 8, the same procedure is applied as is given above, except that the permeabilities and thicknesses of the impermeable layers are ignored.

In such reservoirs, only the pressure buildup at the wellbore can be calculated using the uniform aquifer equations that have been presented.

Radially Varying Permeability

It is possible to have radially varying rock or fluid properties as shown in Figure 9. Such radial variations are most likely to be man-induced. Radial permeability and porosity variations can be caused by formation damage or improvement during well construction or during injection well operation. Such permeability and porosity variations may be deliberately created as in the case of the fracture zones in a nuclear stimulation project or the burned zone of an in-situ oil or oil shale combustion project.

The general equation for determination of an average permeability value, where there are two or more zones of radial permeability is:

$$\overline{k} = \frac{\log(r_e/r_w)}{\sum_{i=1}^{n} \frac{\log(r_i/r_{i-1})}{k_i}} \tag{30}$$

The difficulty in using this solution for pressure buildup calculations is that it requires the knowledge of r_e, the radius to the point at which pressure is that of the undisturbed reservoir. This concept is normally only applied in the so-called steady state flow equations, but can be used in the unsteady state equations presented herein by treating r_e as a varying quantity using the following equation:

$$r_e = \sqrt{\frac{kt}{70.33\phi\mu c}} \tag{31}$$

By inspection, Equation 31 states that r_e is proportional to the square root of time.

As an example, assume that there are two radial zones around an injection well with the following properties and conditions:

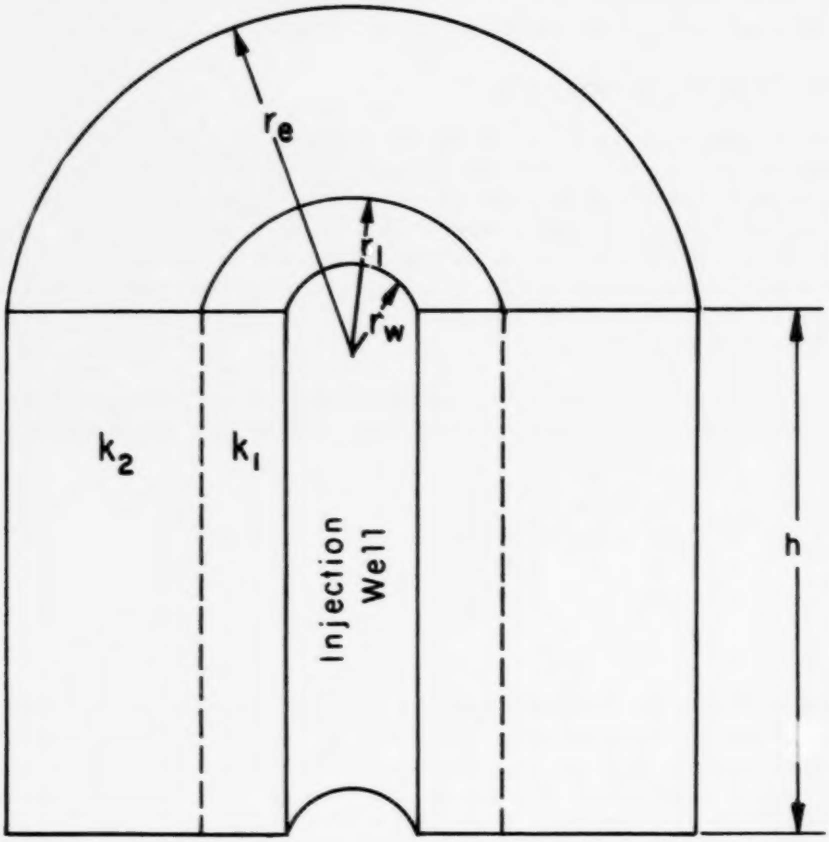

r_e
r_1
r_w
k_2
k_1
Injection Well
h

Figure 9 A reservoir with radially varying permeability.

$r_w = 0.292$ ft

$r_1 = 100$ ft

$r_e = r_2 = ?$

$k_1 = 10$ md

$k_2 = 50$ md

$c = 7.5\text{x}10^{-6}\text{psi}^{-1}$

$t = 30$ days

$\phi = 0.15$

$\mu = 1$ cp

Applying Equation 31,

$$r_e = \sqrt{\frac{50 \text{ x } 30}{70.33\text{x}0.15\text{x}1\text{x}7.5\text{x}10^{-6}}}$$

$r_e = 4{,}354$ ft

Applying Equation 30

$$\overline{k} = \frac{\log 4{,}354/.292}{\frac{\log 100/.292}{10} + \frac{\log 4{,}354/100}{50}} = \frac{4.173}{.2535 + .0327} = 14.58 \text{ md}$$

The average value of permeability to be used for calculations of pressure buildup at the well is then 14.58 md.

FLUIDS OF VARIABLE VISCOSITY

It is common for the fluids being injected to have a viscosity different from the native reservoir fluids. This problem can be handled by considering the effect on hydraulic conductivity caused by the viscosity differences. If flow is considered to be radial, then the average radius to which the injected fluid has traveled after a period of injection is:

$$r_{if} = \sqrt{\frac{5.615qt\beta}{\pi h\phi}} \tag{32}$$

The ratio of the hydraulic conductivity in the radial zone containing the injected fluids to the remainder of the reservoir is:

$$\frac{k}{\mu_{if}} : \frac{k}{\mu_{rf}} \tag{33}$$

This ratio can be rearranged to give a new apparent permeability for the zone containing injected fluid

$$k_a = k\,\frac{\mu_{if}}{\mu_{rf}} \tag{34}$$

The problem can then be treated as if there were zones of varying radial permeability, as is discussed earlier.

DIPPING RESERVOIRS

All of the equations developed previously have incorporated the assumption that the reservoir is horizontal. In cases where the reservoir has a significant dip, the initial pressure (P_{ri}) at a point r, when referenced to the origin is:

$$P_{ri} = P_i + r \tan\theta\,\frac{\gamma_{rf}}{144} \tag{35}$$

Equation 4 would, for example, then become:

$$P_r = P_i + r \tan\theta\,\frac{\gamma_{rf}}{144} + \frac{162.6q\mu\beta}{kh}\log\left(\frac{kt}{70.4\phi\mu c r^2}\right) \tag{36}$$

Assume the following conditions:

$P_i = 0$

$q = 1714$ STB/D

$\beta = 1$

$c = 7.5x10^{-6}psi$

$k = 50$ md

$h = 45$ ft

$\phi = 0.15$

$\mu = 1$ cp

$r = 1000$ ft

$\theta = 10^o$

$\gamma_{rf} = 65.5$ 16/ft^3

$t = 3650$ days

From Equation 36,

$$P_r = 0 + 80.2 + 416.5 = 497 \text{ psi}$$

CHAPTER 4

CALCULATION OF PRESSURE BUILDUP WITH THE PROGRAMMABLE DESK CALCULATOR

The programs listed in Appendix B are written for a Texas Instruments Programmable 59 calculator which allows the storage of programs on magnetic cards.

It is probably safe to assume that most people who will use this publication are familiar with some type of electronic desk calculator. If readers are not, it may prove helpful to read the parts of the Texas Instruments owners manual "Personal Programming" which deal with charging and maintenance of the Texas Instruments Programmable 59 calculator. The section covering keyboard operations will also be profitable, but is not needed for the operation of the programs in this publication. The use of these programs is quite simple. All necessary instructions are contained in this chapter and with the programs in Appendix B. If a reader should wish to modify any of the programs in Appendix B or if a reader should wish to write similar programs of their own, it will then be necessary to become familiar with the programming procedures described in the Texas Instruments publication "Personal Programming" that accompanies the calculator.

PROGRAM ENTRY FROM THE KEYBOARD

To enter one of the programs in Appendix B, turn the calculator on and press the sequence of five keys listed after Partitioning in the program heading. If the program heading says Partitioning normal, skip this step. Next press the LRN key to enter the "learn mode." The display should show 000 00. Now press, in order, each key shown in the Key column of the program listing. As this is done the first three digits of the display should keep pace with the number in the Location column of the program display. The location number shown is that of the step about to be entered.

When all the keys shown in the program listing have been pressed, press LRN again to leave the learn mode. The program is now ready to use according to the User Instructions given with each program. To avoid losing the program when the calculator is turned off (necessitating entering it through the keyboard again) it may be recorded on a magnetic card.

RECORDING A PROGRAM

To record a program on one of the cards accompanying a calculator, hold it with the printed side up and the printing upright. Press the keys 1, 2nd, Write, and insert the card into the lower slot on the right side of the calculator. Keep pushing until the motor starts pulling the card--then let go. When the card stops, pull it out the left side. This records the program steps through location 239. If the program goes beyond this location, turn the card so the printed side is up, but the printing is upside down. Press 2, 2nd, and Write, and insert the card as before. This records steps 240 through 479. If the program continues beyond step 479 a second card will be needed. Hold it with the printed side up and the print upright, press 3, 2nd, and Write, and insert the card as above. This records steps 480 through 719.

The program is now recorded and may be easily re-entered from the card whenever it is needed. For convenience, the key sequence, if any, following Partitioning should be written on the card along with the program title.

PROGRAM ENTRY FROM MAGNETIC CARDS

To enter a program from a magnetic card, turn the calculator on and press the series of five keys (if there is one) following Partitioning in the program listing. Press CLR and insert the card in the same position and into the same slot used for recording. Remove the card when it stops. The display should show 1 for the side which was recorded first (steps 000 through 239). If the display is flashing press CLR, check to be certain the card is clean, and insert it again. If the display still flashes after several trys, see page VII-5 in the owner's manual. It contains some suggestions as to what may be wrong.

To enter the second edge or the next card, hold it in the same position it was in when recorded, press CLR, and insert it as above. The second edge should result in a display of 2, the third (on the second card) should yield 3, and the fourth should cause a display of 4.

PROGRAM EDITING

In the event a mistake is made when a program is being entered from the keyboard, it is important to know how to check and correct the program. While in the learn mode, the SST key may be used to move forward through the program one step at a time without changing the program. Similarly BST may be used to back up one step at a time. If the wrong key was pressed at location 115 for example, use the SST or BST keys, while in the learn mode, to reach location 115 and then simply press the correct key. This replaces the incorrect step in the program with the correct one. If a key has been skipped which should have been entered in location 076, go to that location and press 2nd Ins. This moves the remainder of the program one step leaving location 076 empty. The empty location may now be filled with the omitted key. If an extra key has been pressed somewhere in a program it may be removed by going to that location and pressing 2nd Del. This deletes the unwanted step and moves all subsequent steps in the program to close the gap.

For the purpose of checking a program it should be noted that for any location the two numbers to the right of the location number should match the code shown with that location number in the program listing.

All the editing techniques mentioned thus far are used while in the learn mode. To reach different locations in a program it is sometimes easier to use the GTO (go to) key. This is used while not in the learn mode. Simply press GTO followed by the location number desired. Then press LRN to enter the learn mode for corrections. To illustrate this press GTO 053. If LRN is pressed now, the display will show location 053.

EXAMPLE CALCULATION

As an example of the use of one of the programs, turn to the program titled "Single or multiple wells, constant injection or pumping rate" in Appendix B. The partitioning is normal and so may be ignored. Turning to the listing of the program steps we see that $E_1(x)$ subroutine must be entered first. Turn to the listing of the subroutine titled "Exponential Integral", press the LRN to enter the learn mode, and begin pressing the keys shown in the KEY column. When all steps 000 through 109 have been entered, return to the main program and enter the steps from 110 through 201. Press the LRN key to leave the learn mode. The program should now be ready to use.

To try out the program, enter the following data according to the User Instructions given with the program.

m	1 well	h	45 ft.
P_i	0 psi	ϕ	.15 fraction
q_n	1714 STB/D	μ	1 cp.
r_n	.292 ft.	c	$7.5\text{x}10^{-6}$ 1/psi
t_n	3650 days	β_n	1 RB/STB
k	50 md.	S_n	0

If all the instructions have been followed correctly, the answer displayed will be 1292 psi.

If your efforts produce a different result, re-enter the data and try again. If that doesn't work press GTO 000, enter the learn mode, and start comparing the two digit code for each step with the code shown beside the same location number in the program listing. The section on Program Editing should be helpful at this point. When the mistake has been corrected and the right results are obtained, the program is ready to be recorded on a magnetic card for future use.

CHAPTER 5

CALCULATION OF PRESSURE BUILDUP WITH THE DIGITAL COMPUTER

A computer program has been written for the determination of aquifer pressure behavior under fluid injection and/or production systems. The program is written in ANS FORTRAN and the required data forms are shown on the following pages.

CARD FORMAT

There are four types of formats used to input data in the program.

A Format - for alphanumeric data (data which may be alphabetic letters or numbers; also, sometimes referred to simply as alphameric). Used for titles, etc. Values read with this type of format are not used in calculations and are for print-out clarity.

I Format - used for input of integers. No decimal point is allowed. A group of five columns in the card is used for integers. A group of columns is called a field. Blanks in numerical fields are interpreted as zeros, therefore all integer quantities must be punched in the right-most portion of their allotted fields (i.e., right-justified).

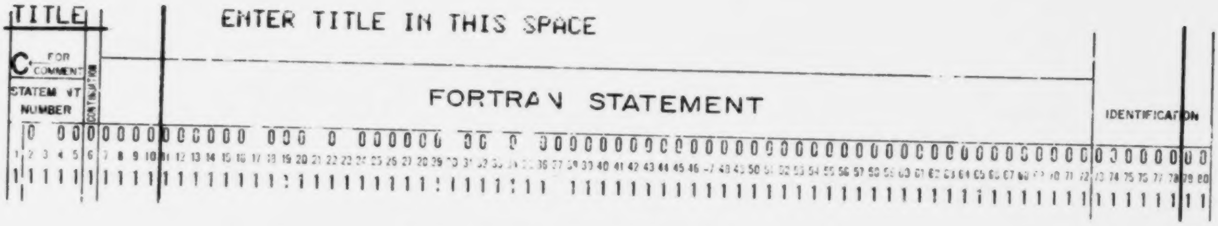
A large number of integer variables are used to indicate to the program a selection between several options. These logical switches require that the number entered be one of the possible values listed (most are restricted to zero and one). Most of the switches are set so that the default (no entry = zero) action is to NOT use a certain feature.

F Format - used for input of real numbers. The decimal point must be punched. Blanks in numerical fields are interpreted as zeroes. A group of ten columns in the card is used for real numbers.

X Format - for skipping spaces. All X formats indicate a card label for user convenience, and may be omitted by the experienced user. It is strongly recommended that the card labels be employed.

TITLE CARD

(There will be one TITLE Card).

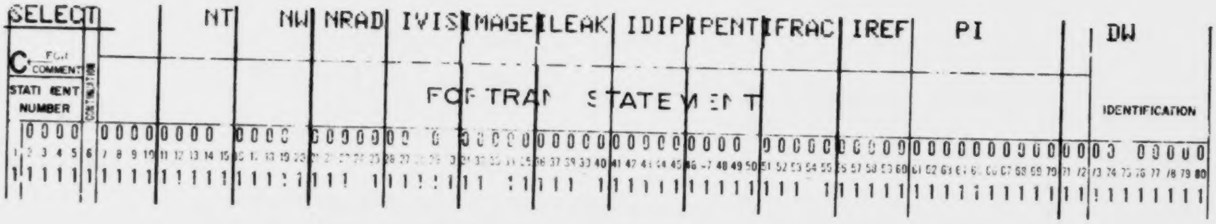

TITLE
ENTER TITLE IN THIS SPACE
C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 17A4)

Enter the title to be printed.

SELECT CARD

(There will be one SELECT card)



FORMAT (10X, 10I5, 2F10.2)

NT - Number of time entries at which pressures will be calculated.

NW - Number of wells to be included when determining pressures.

NRAD - Number of distances at which pressures will be calculated.

IVIS - Switch for variable fluid viscosity
= 0, constant viscosity
= 1, viscosity varies with distance

IMAGE - Switch for boundary effects
= 0, no image wells
= 1, image wells will be included

ILEAK - Aquifer leakage indicator
= 0, no leakage
= 1, leakage exists

IDIP - Switch to account for dipping beds
= 0, horizontal bed
= 1, dipping bed

IPENT - Indicator for partially penetrating wells
= 0, wells completed throughout bed
= 1, partial penetration exists

IFRAC - Fracture analysis switch
= 0, no fractures
= 1, vertical fracture solution
= 2, horizontal fracture solution

IREF - Well to be used in printing distances to pressure calculations (default value is 1)

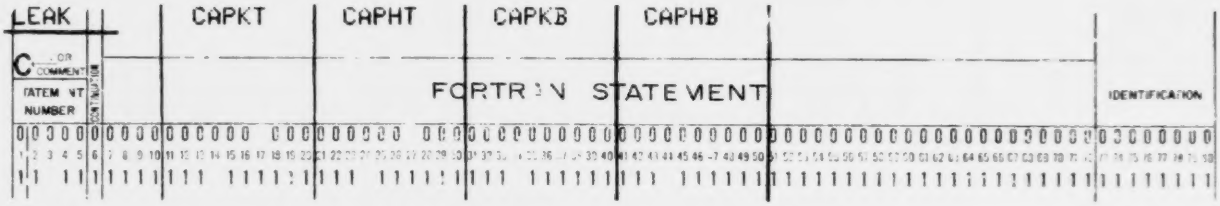
PI - Initial pressure, psi

DW = Water density, lb./ft.^{3}

LEAK CARD

If ILEAK = 0 (on the
SELECT card), omit this card.

(There will be one LEAK card, when needed).


LEAK
CAPKT
CAPHT
CAPKB
CAPHB
C FOR COMMENT
STATEMENT NUMBER
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 4F10.3)

CAPKT - Permeability of overlying leaky bed, md. (if no leakage occurs, leave blank)

CAPHT - Thickness of overlying leaky bed, ft.

CAPKB - Permeability of underlying leaky bed, md. (if no leakage occurs, leave blank).

CAPHB - Thickness of underlying leaky bed, ft.

IMAGE CARD

If IMAGE = 0 (on the SELECT card),
omit this card.

(There will be one IMAGE card, when needed)

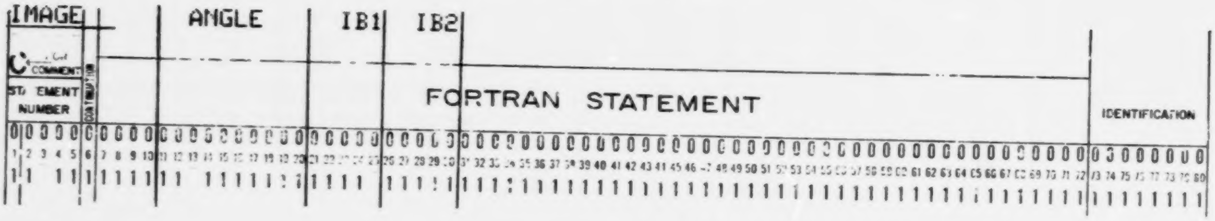


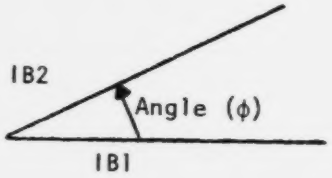
IMAGE
ANGLE
IB1
IB2
COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, F10.2, 2I5)

ANGLE - Angle of intersection between boundaries, degrees (for a single boundary, enter 180; and for parallel boundaries, enter 360)

IB1 - Indicator for lower boundary
= 0, sealing boundary
= 1, leaky boundary

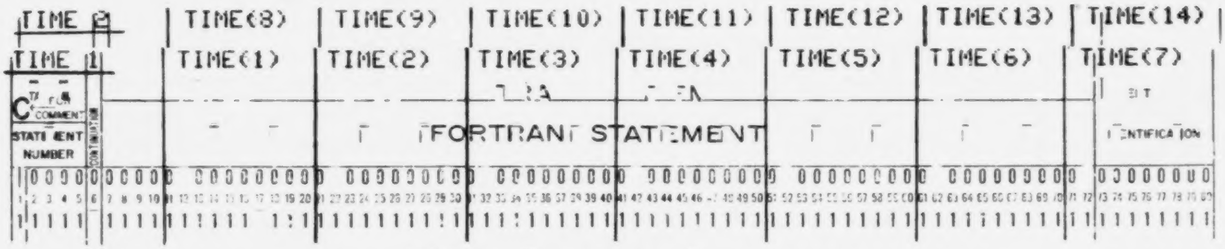
IB2 - Indicator for upper boundary
= 0, sealing boundary
= 1, leaky boundary


IB2
Angle (ϕ)
IB1

NOTE: For the single boundary case (Angle = 180), only IB1 is required; for the case of parallel boundaries (ANGLE = 360), IB1 is the left boundary and IB2 is the right boundary (top and bottom may be substituted for left and right, respectively).

TIME CARD

(There will be as many TIME cards as required for NT values, 7 values per card).


TIME 2
TIME(8)
TIME(9)
TIME(10)
TIME(11)
TIME(12)
TIME(13)
TIME(14)
TIME 1
TIME(1)
TIME(2)
TIME(3)
TIME(4)
TIME(5)
TIME(6)
TIME(7)
C FOR COMMENT
STATEMENT NUMBER
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 7F10.3)

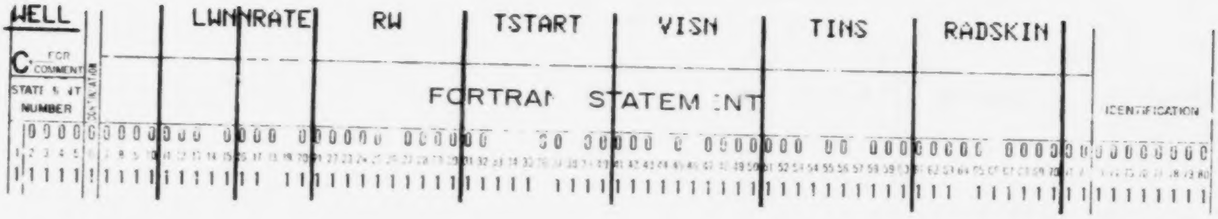
TIME(1) - Cumulative time at which pressure is calculated, days

TIME(2) - Cumulative time at which pressure is calculated, days

TIME(3) - etc.

WELL CARDS

(There will be NW well cards, each
card followed by the options selected)


WELL
LWN
NRATE
RW
TSTART
VISN
TINS
RADSKIN
C FOR COMMENT
STATEMENT NUMBER
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 2I5, 5F10.0)

LWN - Well number (number wells sequentially from 1 to NW)

NRATE - Number of rates for this well

RW - Wellbore radius, in. (default value is 3")

TSTART - Time to start of first rate for this well, days (relates all wells to same start time)

VISN - Viscosity of injected fluid, cp. (used if IVIS = 1 on the SELECT card)

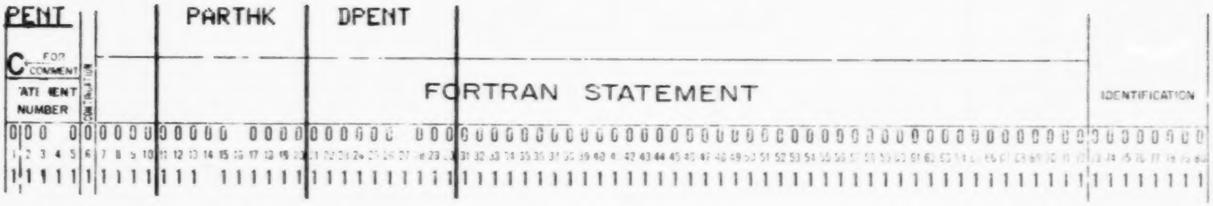
TINS - Time to start of injection of VISN, cp.

RADSKIN - Radius of skin effect, ft. (default value is 100')

PENT CARD

If IPENT = 0 (on the SELECT card), omit this card.

(There will be one PENT card per well, when required).


PENT
PARTHK
DPENT
C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 2F10.0)

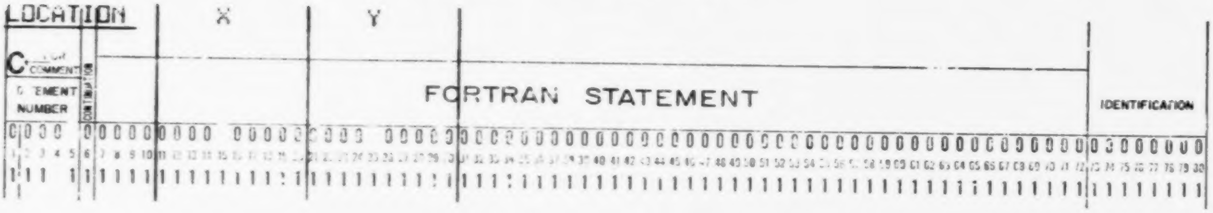
PARTHK - Length of partial penetration, ft.

DPENT - Distance from top of reservoir to top of partial penetration, ft.

LOCATION CARD

IF IMAGE = 0 (on the
SELECT card), omit this card.

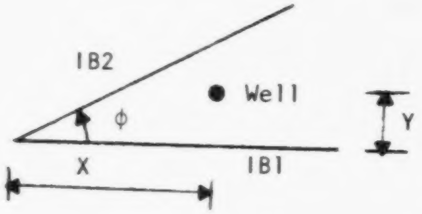
(There will be one LOCATION card
per well, when required).


LOCATION
X
Y
C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 2F10.3)

X - Horizontal distance of well from boundary intersection, ft.

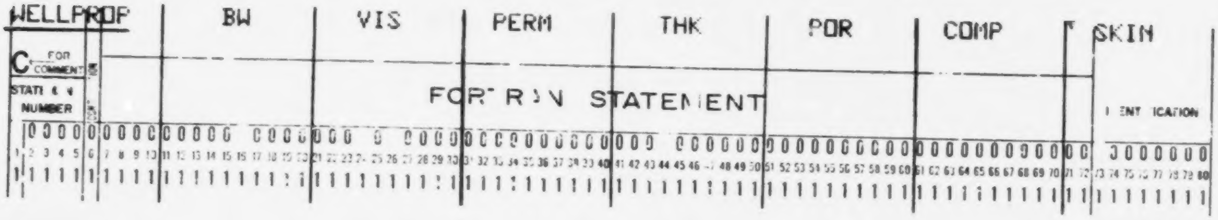
Y - Vertical distance of well from lower boundary, ft.


IB2
Well
ϕ
Y
X
IB1

NOTE: For parallel boundaries, X(1) is the distance to IB1 and Y(1) is the distance to IB2; thus well #1 becomes the origin of the parallel boundaries system and all remaining locations are measured with respect to well #1 (i.e., X(2) is the horizontal distance from well #1 to well #2, etc.).

WELLPROP CARD

(There will be one WELLPROP card for each well)


WELLPROP
BW
VIS
PERM
THK
POR
COMP
SKIN
C FOR COMMENT
STATEMENT NUMBER
FORTRAN STATEMENT
IDENTIFICATION

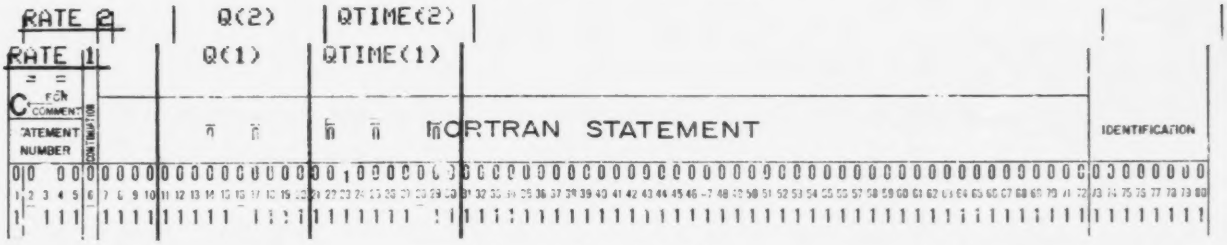
FORMAT (10X, 7F10.3)

BW -	Formation volume factor of injected (or produced) fluid, RVB/STB.
VIS -	Reservoir fluid viscosity, cp.
PERM -	Areal effective permeability, md.
THK -	Reservoir thickness, ft.
POR -	Reservoir porosity, fraction
COMP -	Total system compressibility, bbl/MMbbl/psi
SKIN -	Wellbore skin factor

When observing a highly compressible system (e.g., a gas reservoir), BW should be evaluated at an average reservoir pressure; if BW cannot be estimated, enter a value of 1.0, run the program, check the calculated pressures, re-evaluate BW and run the program a second time. For a gas system, BW may have units of RVB/MCF for well rates in MCF/day.

RATE CARDS

(There will be NRATE RATE cards per well
as specified on the WELL card)


RATE 2
Q(2)
QTIME(2)
RATE 1
Q(1)
QTIME(1)
C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 2F10.3)

Q(1) - Rate of well until QTIME(1), STB/day, (positive for injection and negative for production).

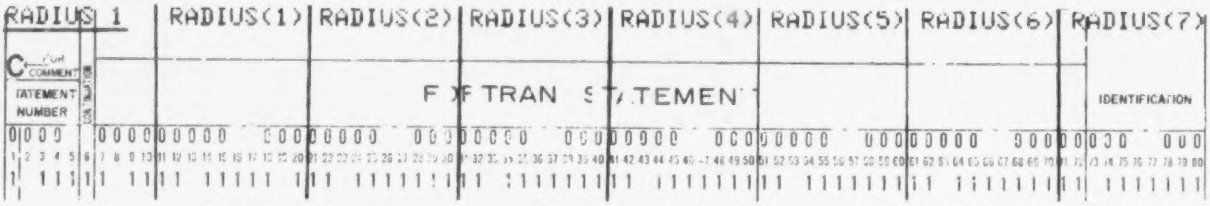
QTIME(1) - Cumulative time to end of rate Q(1), days (all times are measured from TSTART on well #1 in multiple well situations).

Q(2) - etc.

RADIUS CARDS

IF IFRAC > 0 or IMAGE = 0 (on the
SELECT card), omit this card.

(There will be NRAD values as
specified on the SELECT card)


RADIUS 1
RADIUS(1)
RADIUS(2)
RADIUS(3)
RADIUS(4)
RADIUS(5)
RADIUS(6)
RADIUS(7)
C FOR COMMENT
STATEMENT NUMBER
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 7F10.3)

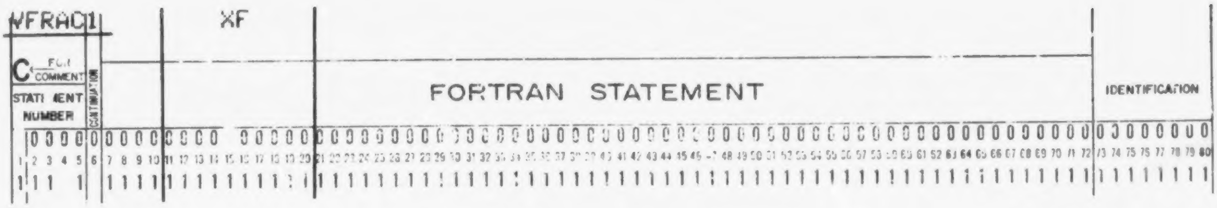
RADIUS(1) - Distance from well to observation point of pressure calculation, ft.

RADIUS(2) - etc.

VFRAC1 CARD

If IFRAC ≠ 1, skip this page.

(There will be one VFRAC1 card per well when required).

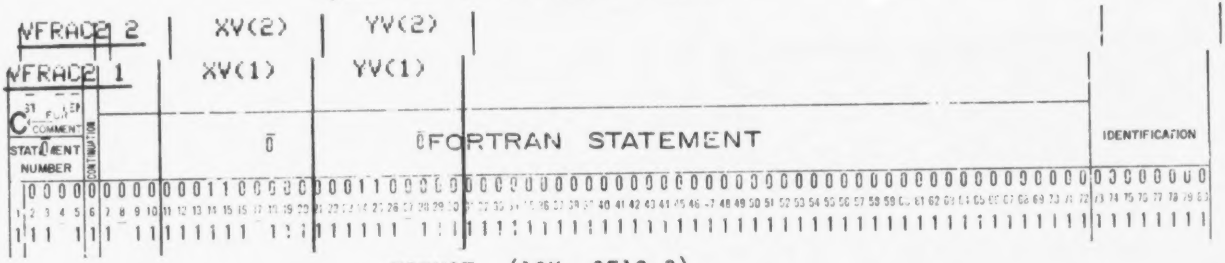

VFRAC1
XF
C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, F10.3)

XF - Fracture length (or 1/2 length from wellbore), ft.

VFRAC2 CARDS

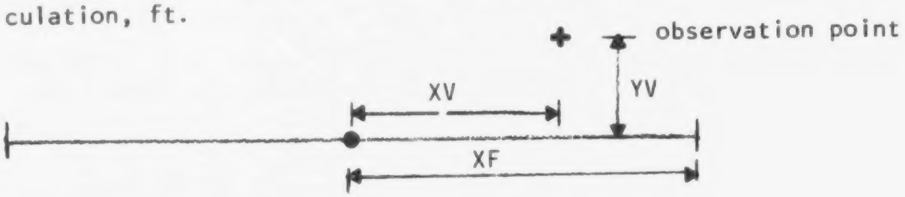
(There will be NRAD cards as specified on the SELECT card).


VFRAC2 2
XV(2)
YV(2)
VFRAC2 1
XV(1)
YV(1)
C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 2F10.3)

XV(1) - Horizontal distance from well to observation point of pressure calculation, ft.

YV(1) - Distance from fracture to observation point of pressure calculation, ft.

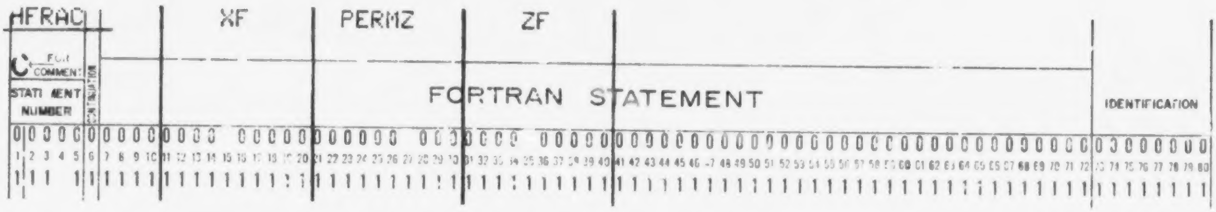

observation point
XV
YV
XF

XV(2) - etc.

HFRAC CARD

IF IFRAC ≠ 2, skip this page.

(There will be one card per well, when required)


HFRAC
XF
PERMZ
ZF
C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION

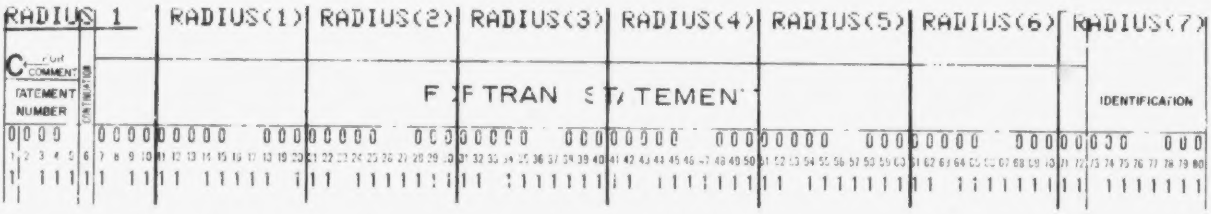
FORMAT (10X, 3F10.3)

XF - Radius of fracture, ft.

PERMZ - Vertical permeability of formation, md.

ZF - Distance from fracture to bottom of reservoir, ft.

RADIUS CARDS


RADIUS 1
RADIUS(1)
RADIUS(2)
RADIUS(3)
RADIUS(4)
RADIUS(5)
RADIUS(6)
RADIUS(7)
C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 7F10.3)

RADIUS(1) - Distance from well to observation point, ft.

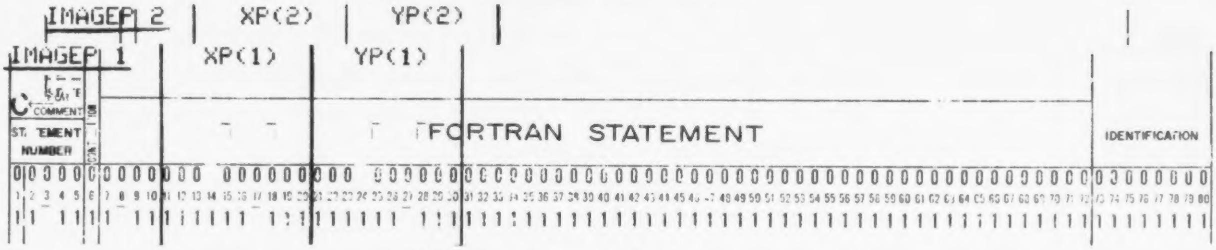
RADIUS(2) - etc.

NOTE: This is the last possible card in the well sequence; return to the well card until NW (on the SELECT card) well sets have been input.

IMAGEP CARDS

If IMAGE = 0, omit these cards

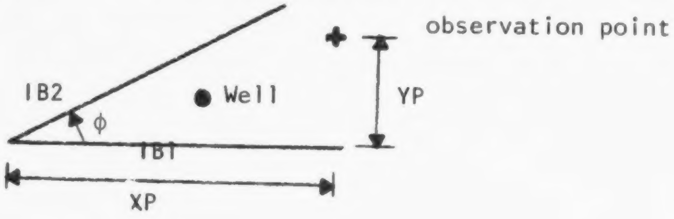
(There will be NRAD cards).


IMAGEP 2
XP(2)
YP(2)
IMAGEP 1
XP(1)
YP(1)
COMMENT
STATEMENT NUMBER
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 2F10.3)

XP(1) - Horizontal distance to observation point from boundary intersection, ft.

YP(1) - Vertical distance to observation point from lower boundary, ft.


observation point
IB2
Well
YP
ϕ
IB1
XP

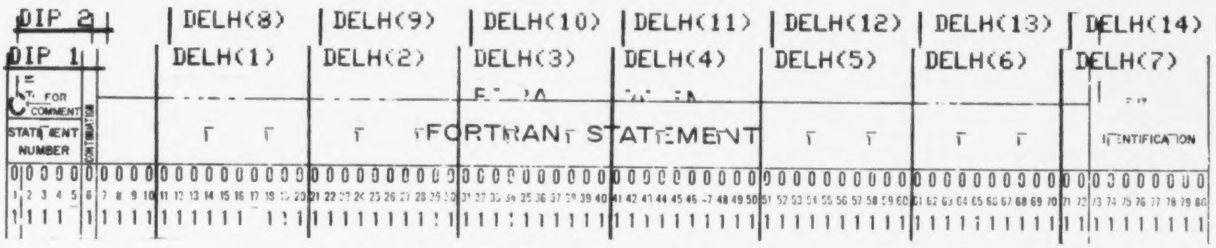
XP(2) - etc.

NOTE: For the parallel boundaries case, XP and YP are distances from well #1.

DIP CARD

If IDIP = 0 (on the SELECT card), omit this card.

(There will be NRAD values).


DIP 2
DELH(8)
DELH(9)
DELH(10)
DELH(11)
DELH(12)
DELH(13)
DELH(14)
DIP 1
DELH(1)
DELH(2)
DELH(3)
DELH(4)
DELH(5)
DELH(6)
DELH(7)
C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION

FORMAT (10X, 7F10.3)

DELH(1) - Vertical distance from wellbore to observation point for pressure calculation (a positive value indicates a lower position), ft.

DELH(2) - etc.

EXAMPLES

Single Well - Constant Rate

Two Well - Constant Rate

Single Well - Variable Rate

Single Well - Skin Factor (damage)

Single Well - Skin Factor (improvement)

Single Well - Partial Penetration

Single Well - Vertical Fracture (wellbore pressure)

Single Well - Vertical Fracture (reservoir pressure)

Single Well - Horizontal Fracture

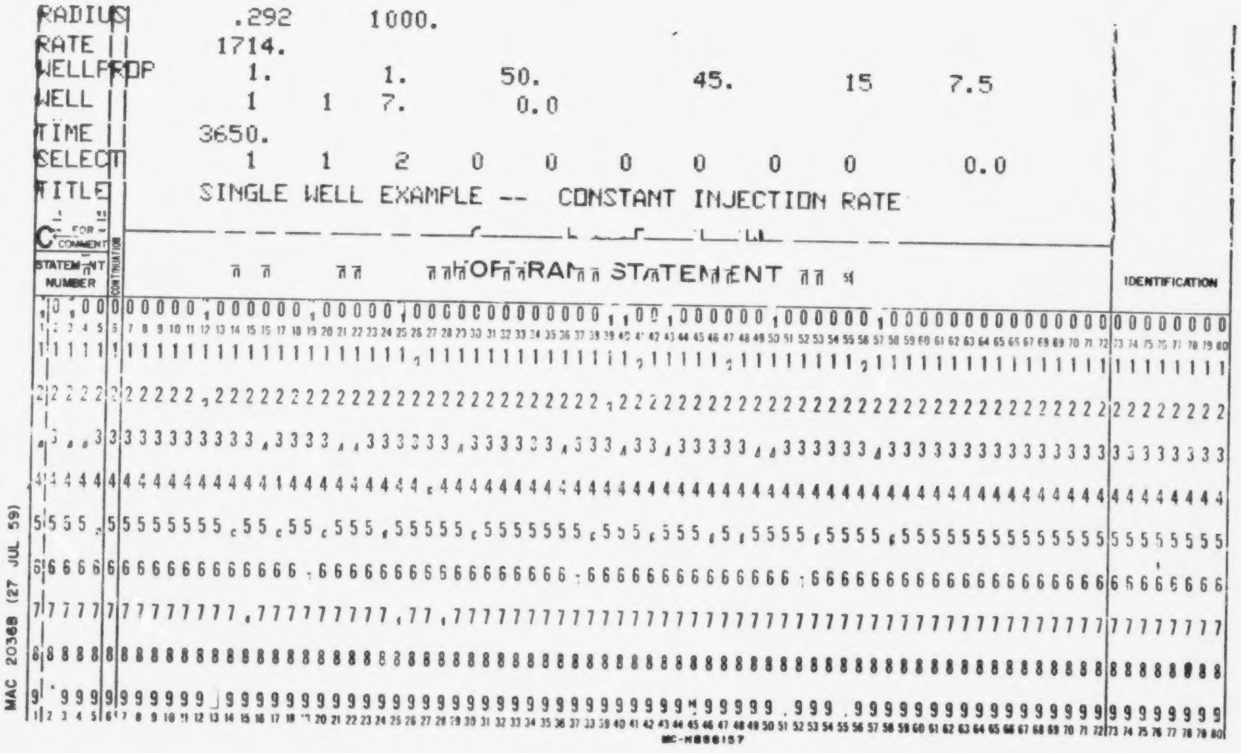
Single Well - Leaky Aquifer (Case 1)

Single Well - Leaky Aquifer (Case 2)

Single Well - Intersecting Sealing Faults

Single Well - Parallel Sealing Faults

Single Well - Dipping Reservoir



```
RADIUS       .292      1000.
RATE        1714.
WELLPROP       1.         1.       50.             45.        15      7.5
WELL           1     1    7.        0.0
TIME        3650.
SELECT         1     1    2     0     0     0     0     0     0         0.0
TITLE       SINGLE WELL EXAMPLE --  CONSTANT INJECTION RATE
```

C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION
MAC 20368 (27 JUL 59)

```
                                                  DETERMINATION OF
                                             AQUIFER PRESSURE BEHAVIOR
                                               UNDER FLUID INJECTION
                                             AND/OR PRODUCTION SYSTEMS

 SINGLE WELL EXAMPLE --  CONSTANT INJECTION RATE



 INITIALIZATION DATA:

      NT=              1    NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
      NW=              1    NUMBER OF WELLS TO BE CONSIDERED
      NRAD=            2    NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED



 AQUIFER CHARACTERISTICS TO BE CONSIDERED:

      IVIS=            0    INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
      IMAGE=           0    AQUIFER CONFINED BY BOUNDARIES?  NO
      ILEAK=           0    VERTICAL AQUIFER LEAKAGE?  NO
      IDIP=            0    DIPPING BED?  NO
      IPENT=           0    WELLS PARTIALLY PENETRATING BED?  NO
      IFRAC=           0    FRACTURE ANALYSIS?  NO
      IREF=            1    REFERENCE WELL FOR PRINTING



 GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

      CAPKT=         0.0    PERMEABILITY OF OVERLYING BED (MD)
      CAPHT=         0.0    THICKNESS OF OVERLYING BED (FT)
      CAPKB=         0.0    PERMEABILITY OF UNDERLYING BED (MD)
      CAPHB=         0.0    THICKNESS OF UNDERLYING BED (FT)
      ANGLE=         0.0    ANGLE OF BOUNDARY INTERSECTION (DEG)
      IB1=             0    BOUNDARY 1 SEALING OR LEAKING? SEAL
      IB2=             0    BOUNDARY 2 SEALING OR LEAKING? SEAL
      PI=            0.0    INTIAL RESERVOIR PRESSURE (PSI)
      DW=            0.0    DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                    RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                           INPUT DATA FOR WELL    1

TSTART=          0.0   TIME TO START OF FIRST RATE (DAYS)
PARTHK=          0.0   LENGTH OF WELL PENETRATION (FT)
PERMZ=           0.0   VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=       100.00   RADIUS EFFECTED BY SKIN (FT)
PERM=          50.00   AREAL RESERVOIR PERMEABILITY (MD)
NRATE=             1   NUMBER OF RATES
VIS=           1.000   VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=            0.0   SKIN FACTOR AT WELLBORE
POR=           0.150   RESERVOIR POROSITY (FRACTION)
TINS=            0.0   TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=           45.00   RESERVOIR THICKNESS (FT)
VISN=          0.0     NEW FLUID VISCOSITY (CP)
BW=             1.00   FORMATION VOLUME FACTOR (RB/STB)
COMP=     0.00000750   SYSTEM COMPRESSIBILITY (1/PSI)
RW=            0.583   WELLBORE RADIUS (FT)
X=               0.0   REAL WELL X-LOCATION (FT)
XF=            0.0     FRACTURE LENGTH (FT)
Y=               0.0   REAL WELL Y-LOCATION (FT)
ZF=            0.0     DISTANCE FROM HORIZONTAL FRACTURE
DPENT=           0.0   DISTANCE FROM TOP OF ZONE TO TOP OF
                       PENETRATION (FT) (FT)


                                                  CUMULATIVE TIME
                     RATE        WELL RATE        TO END OF RATE
                    NUMBER       (STB/DAY)            DAYS

                      1           1714.00              0.0

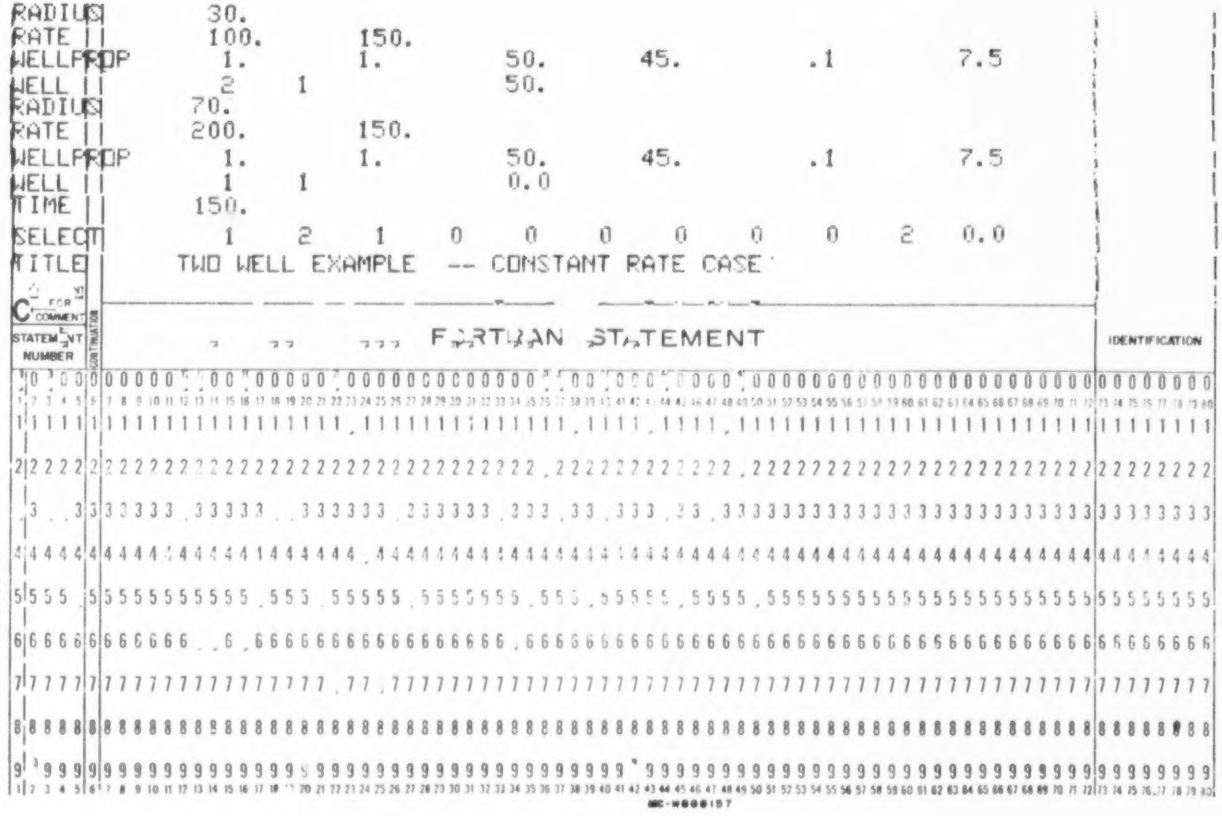

                       DISTANCE TO POINT X FOR WELL    1
                                   CHANGE IN
                       POINT       ELEVATION             RADIUS
                      NUMBER          (FT)                (FT)

                         1            0.0                  0.29
                         2            0.0               1000.00
```

```
 PRESSURE AT TIME   3650.000 (DAYS)

 POINT         RADIUS FROM          PRESSURE
NUMBER       REFERENCE WELL          (PSIA)

   1                 0.292          1291.857
   2              1000.000           416.441
```



```
RADIUS      30.
RATE        100.       150.
WELLPROP     1.         1.         50.        45.        .1         7.5
WELL         2     1               50.
RADIUS     70.
RATE       200.        150.
WELLPROP     1.         1.         50.        45.        .1         7.5
WELL         1     1               0.0
TIME       150.
SELECT       1     2     1     0     0     0     0     0     0     2  0.0
TITLE     TWO WELL EXAMPLE  -- CONSTANT RATE CASE
```

C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION
MAC 2036B (27 JUL 59)

```
                                          DETERMINATION OF
                                       AQUIFER PRESSURE BEHAVIOR
                                         UNDER FLUID INJECTION
                                       AND/OR PRODUCTION SYSTEMS

 TWO WELL EXAMPLE  -- CONSTANT RATF CASE



INITIALIZATION DATA:

     NT=          1    NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
     NW=          2    NUMBER OF WELLS TO BE CONSIDERED
     NRAD=        1    NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


AQUIFER CHARACTERISTICS TO BE CONSIDERED:

     IVIS=        0    INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
     IMAGE=       0    AQUIFER CONFINED BY BOUNDARIES?  NO
     ILEAK=       0    VERTICAL AQUIFER LFAKAGE?  NO
     IDIP=        0    DIPPING BED?  NO
     IPENT=       0    WELLS PARTIALLY PENETRATING BED?  NO
     IFRAC=       0    FRACTURE ANALYSIS?  NO
     IREF=        2    RFFERENCE WELL FOR PRINTING


GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

     CAPKT=      0.0   PERMEABILITY OF OVERLYING BED (MD)
     CAPHT=      0.0   THICKNESS OF OVERLYING BED (FT)
     CAPKB=      0.0   PERMEABILITY OF UNDERLYING BED (MD)
     CAPHB=      0.0   THICKNESS OF UNDERLYING BED (FT)
     ANGLE=      0.0   ANGLE OF BOUNDARY INTERSECTION (DEG)
     IB1=          0   BOUNDARY 1 SEALING OR LEAKING? SEAL
     IB2=          0   BOUNDARY 2 SEALING OR LEAKING? SEAL
     PI=         0.0   INTIAL RESFRVOIR PRESSURE (PSI)
     DW=         0.0   DENSITY OF RFSERVOIR FLUID (LB./CU. FT.)
```

```
                    RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                          INPUT DATA FOR WELL    1

TSTART=        0.0  TIME TO START OF FIRST RATE (DAYS)
PARTHK=        0.0  LENGTH OF WELL PENETRATION (FT)
PERMZ=         0.0  VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=     100.00 RADIUS EFFECTED BY SKIN (FT)
PERM=        50.00 AREAL RESERVOIR PERMEABILITY (MD)
NRATE=           1 NUMBER OF RATES
VIS=         1.000 VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=          0.0  SKIN FACTOR AT WELLBORE
POR=         0.100 RESERVOIR POROSITY (FRACTION)
TINS=          0.0  TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=         45.00 RESERVOIR THICKNESS (FT)
VISN=        0.0   NEW FLUID VISCOSITY (CP)
BW=           1.00 FORMATION VOLUME FACTOR (RB/STB)
COMP=   0.00000750 SYSTEM COMPRESSIBILITY (1/PSI)
RW=          0.250 WELLBORE RADIUS (FT)
X=             0.0  REAL WELL X-LOCATION (FT)
XF=          0.0    FRACTURE LENGTH (FT)
Y=             0.0  REAL WELL Y-LOCATION (FT)
ZF=          0.0    DISTANCE FROM HORIZONTAL FRACTURE
DPENT=         0.0  DISTANCE FROM TOP OF ZONE TO TOP OF
                    PENETRATION (FT) (FT)


                                                CUMULATIVE TIME
                   RATE        WELL RATE        TO END OF RATE
                  NUMBER       (STB/DAY)             DAYS

                   1            200.00              150.00
```

```
                    RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                           INPUT DATA FOR WELL    2

TSTART=       50.00 TIME TO START OF FIRST RATE (DAYS)
PARTHK=        0.0  LENGTH OF WELL PENETRATION (FT)
PERMZ=         0.0  VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=      100.00 RADIUS EFFECTED BY SKIN (FT)
PERM=         50.00 AREAL RESERVOIR PERMEABILITY (MD)
NRATE=            1 NUMBER OF RATES
VIS=          1.000 VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=          0.0  SKIN FACTOR AT WELLBORE
POR=          0.100 RESERVOIR POROSITY (FRACTION)
TINS=          0.0  TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=          45.00 RESERVOIR THICKNESS (FT)
VISN=          0.0  NEW FLUID VISCOSITY (CP)
BW=            1.00 FORMATION VOLUME FACTOR (RB/STB)
COMP=    0.00000750 SYSTEM COMPRESSIBILITY (1/PSI)
RW=           0.250 WELLBORE RADIUS (FT)
X=             0.0  REAL WELL X-LOCATION (FT)
XF=            0.0  FRACTURE LENGTH (FT)
Y=             0.0  REAL WELL Y-LOCATION (FT)
ZF=            0.0  DISTANCE FROM HORIZONTAL FRACTURE
DPENT=         0.0  DISTANCE FROM TOP OF ZONE TO TOP OF
                    PENETRATION (FT) (FT)


                                                     CUMULATIVE TIME
                    RATE         WELL RATE            TO END OF RATE
                   NUMBER        (STB/DAY)                DAYS

                     1             100.00                150.00


                      DISTANCE TO POINT X FOR WELL     1
                                    CHANGE IN
                      POINT         ELEVATION                RADIUS
                     NUMBER           (FT)                    (FT)

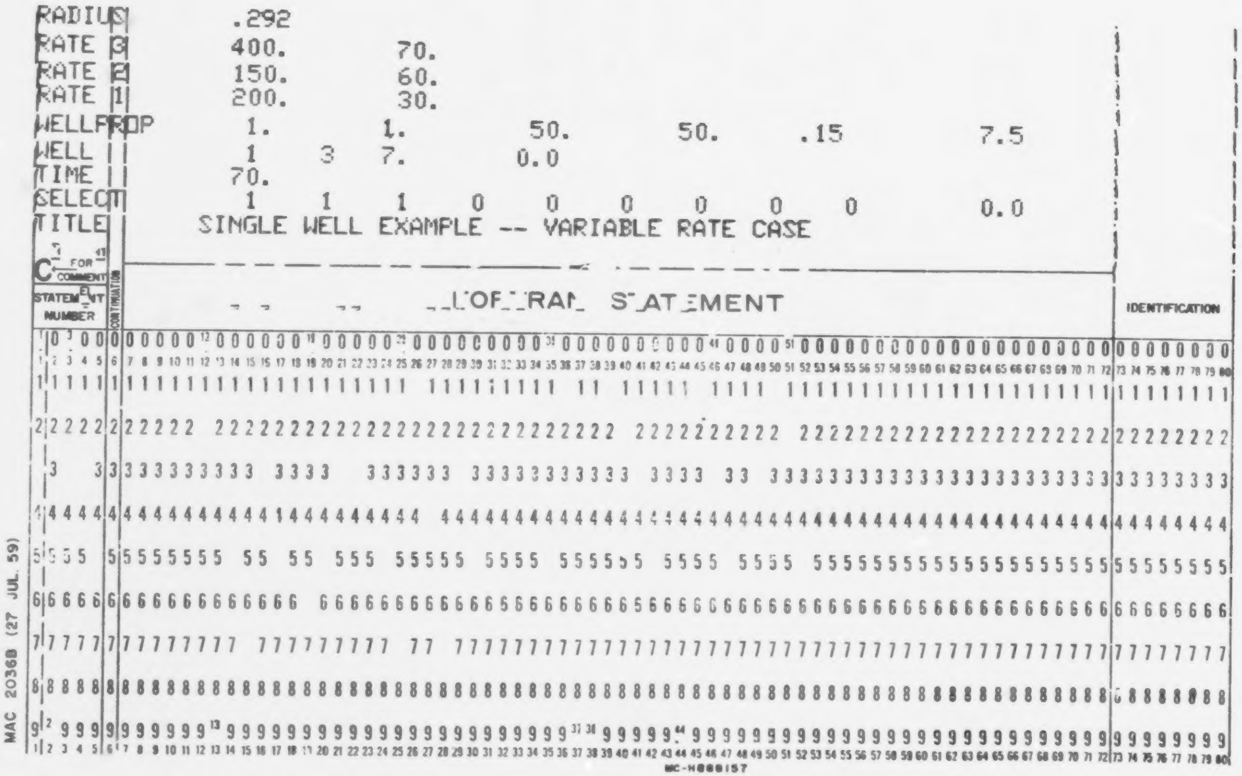
                        1              0.0                    70.00


                      DISTANCE TO POINT X FOR WELL     2
                                    CHANGE IN
                      POINT         ELEVATION                RADIUS
                     NUMBER           (FT)                    (FT)

                        1              0.0                    30.00
```

```
 PRESSURE AT TIME    150.000 (DAYS)

POINT        RADIUS FROM         PRESSURE
NUMBER     REFERENCE WELL        (PSIA)
  1                 30.000       100.768
```



```
RADIUS        .292
RATE  3       400.        70.
RATE  2       150.        60.
RATE  1       200.        30.
WELLPROP        1.         1.         50.         50.      .15         7.5
WELL            1     3    7.        0.0
TIME          70.
SELECT          1     1    1     0     0     0     0     0     0      0.0
TITLE        SINGLE WELL EXAMPLE -- VARIABLE RATE CASE
```

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```
                                          DETERMINATION OF
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                                        UNDER FLUID INJECTION
                                      AND/OR PRODUCTION SYSTEMS

   SINGLE WELL EXAMPLE -- VARIABLE RATE CASE



  INITIALIZATION DATA:

      NT=             1    NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
      NW=             1    NUMBER OF WELLS TO BE CONSIDERED
      NRAD=           1    NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


  AQUIFER CHARACTERISTICS TO BE CONSIDERED:

      IVIS=           0    INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
      IMAGE=          0    AQUIFER CONFINED BY BOUNDARIES?  NO
      ILEAK=          0    VERTICAL AQUIFER LEAKAGE?  NO
      IDIP=           0    DIPPING BED?  NO
      IPENT=          0    WELLS PARTIALLY PENETRATING BED?  NO
      IFRAC=          0    FRACTURE ANALYSIS?  NO
      IREF=           1    REFERENCE WELL FOR PRINTING


  GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

      CAPKT=        0.0    PERMEABILITY OF OVERLYING BED (MD)
      CAPHT=        0.0    THICKNESS OF OVERLYING BED (FT)
      CAPKB=        0.0    PERMEABILITY OF UNDERLYING BED (MD)
      CAPHB=        0.0    THICKNESS OF UNDERLYING BED (FT)
      ANGLE=        0.0    ANGLE OF BOUNDARY INTERSECTION (DEG)
      IB1=            0    BOUNDARY 1 SEALING OR LEAKING? SEAL
      IB2=            0    BOUNDARY 2 SEALING OR LEAKING? SEAL
      PI=           0.0    INTIAL RESERVOIR PRESSURE (PSI)
      DW=           0.0    DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                       RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                              INPUT DATA FOR WELL    1

TSTART=         0.0  TIME TO START OF FIRST RATE (DAYS)
PARTHK=         0.0  LENGTH OF WELL PENETRATION (FT)
PERMZ=          0.0  VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=      100.00  RADIUS EFFECTED BY SKIN (FT)
PERM=         50.00  AREAL RESERVOIR PERMEABILITY (MD)
NRATE=            3  NUMBER OF RATES
VIS=          1.000  VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=         0.0    SKIN FACTOR AT WELLBORE
POR=          0.150  RESERVOIR POROSITY (FRACTION)
TINS=           0.0  TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=          50.00  RESERVOIR THICKNESS (FT)
VISN=         0.0    NEW FLUID VISCOSITY (CP)
BW=            1.00  FORMATION VOLUME FACTOR (RB/STB)
COMP=    0.00000750  SYSTEM COMPRESSIBILITY (1/PSI)
RW=           0.583  WELLBORE RADIUS (FT)
X=              0.0  REAL WELL X-LOCATION (FT)
XF=           0.0    FRACTURE LENGTH (FT)
Y=              0.0  REAL WELL Y-LOCATION (FT)
ZF=           0.0    DISTANCE FROM HORIZONTAL FRACTURE
DPENT=          0.0  DISTANCE FROM TOP OF ZONE TO TOP OF
                     PENETRATION (FT) (FT)


                                                      CUMULATIVE TIME
                         RATE       WELL RATE         TO END OF RATE
                        NUMBER      (STB/DAY)             DAYS

                          1          200.00              30.00
                          2          150.00              60.00
                          3          400.00              70.00

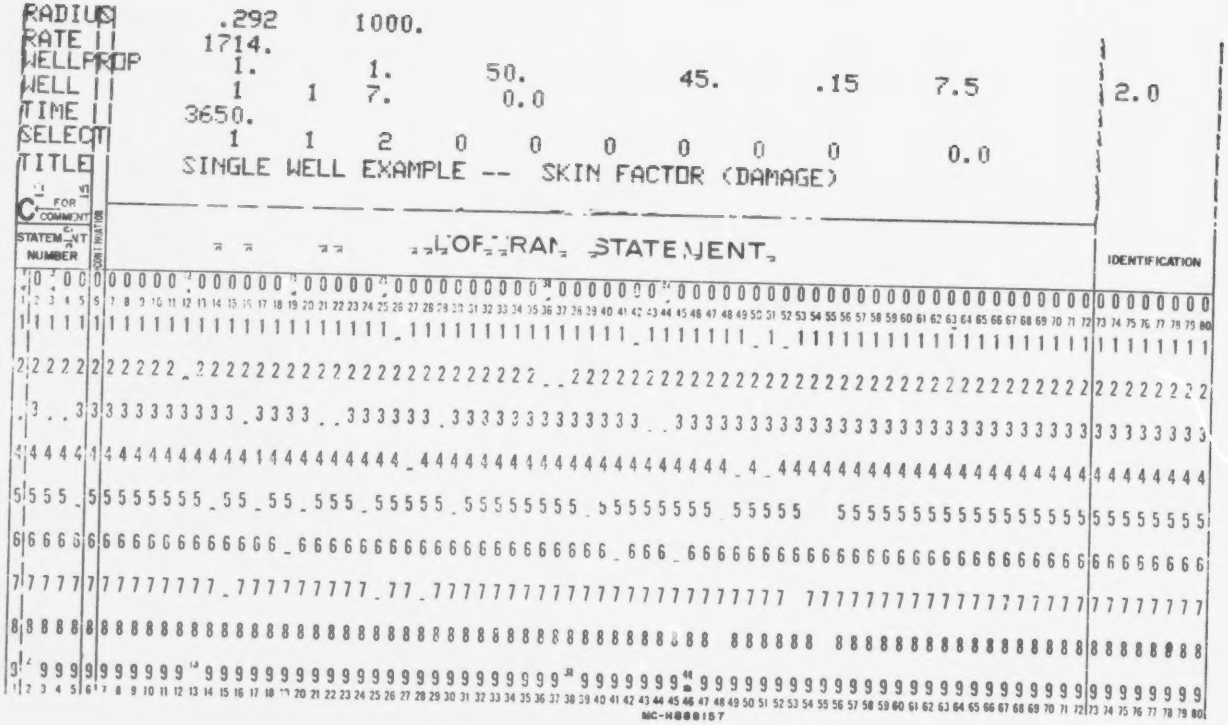

                           DISTANCE TO POINT X FOR WELL     1
                                         CHANGE IN
                          POINT          ELEVATION              RADIUS
                          NUMBER           (FT)                  (FT)

                            1               0.0                   0.29
```

```
PRESSURE AT TIME      70.000 (DAYS)

  POINT        RADIUS FROM          PRESSURE
 NUMBER     REFERENCE WELL          (PSIA)

   1                 0.292         213.723
```



```
                                          DETERMINATION OF
                                      AQUIFER PRESSURE BEHAVIOR
                                        UNDER FLUID INJECTION
                                      AND/OR PRODUCTION SYSTEMS

  SINGLE WELL EXAMPLE --  SKIN FACTOR (DAMAGE)


 INITIALIZATION DATA:

     NT=              1   NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
     NW=              1   NUMBER OF WELLS TO BE CONSIDERED
     NRAD=            2   NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


 AQUIFER CHARACTERISTICS TO BE CONSIDERED:

     IVIS=            0   INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
     IMAGE=           0   AQUIFER CONFINED BY BOUNDARIES?  NO
     ILEAK=           0   VERTICAL AQUIFER LEAKAGE?  NO
     IDIP=            0   DIPPING BED?  NO
     IPENT=           0   WELLS PARTIALLY PENETRATING BED?  NO
     IFRAC=           0   FRACTURE ANALYSIS?  NO
     IREF=            1   REFERENCE WELL FOR PRINTING


 GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

     CAPKT=         0.0   PERMEABILITY OF OVERLYING BED (MD)
     CAPHT=         0.0   THICKNESS OF OVERLYING BED (FT)
     CAPKB=         0.0   PERMEABILITY OF UNDERLYING BED (MD)
     CAPHB=         0.0   THICKNESS OF UNDERLYING BED (FT)
     ANGLE=         0.0   ANGLE OF BOUNDARY INTERSECTION (DEG)
     IB1=             0   BOUNDARY 1 SEALING OR LEAKING? SEAL
     IB2=             0   BOUNDARY 2 SEALING OR LEAKING? SEAL
     PI=            0.0   INTIAL RESERVOIR PRESSURE (PSI)
     DW=            0.0   DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                       RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                                INPUT DATA FOR WELL   1

TSTART=         0.0  TIME TO START OF FIRST RATE (DAYS)
PARTHK=         0.0  LENGTH OF WELL PENETRATION (FT)
PERMZ=          0.0  VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=      100.00  RADIUS EFFECTED BY SKIN (FT)
PERM=         50.00  AREAL RESERVOIR PERMEABILITY (MD)
NRATE=            1  NUMBER OF RATES
VIS=          1.000  VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=          2.00  SKIN FACTOR AT WELLBORE
POR=          0.150  RESERVOIR POROSITY (FRACTION)
TINS=           0.0  TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=          45.00  RESERVOIR THICKNESS (FT)
VISN=         0.0    NEW FLUID VISCOSITY (CP)
BW=            1.00  FORMATION VOLUME FACTOR (RB/STB)
COMP=    0.00000750  SYSTEM COMPRESSIBILITY (1/PSI)
RW=           0.583  WELLBORE RADIUS (FT)
X=              0.0  REAL WELL X-LOCATION (FT)
XF=           0.0    FRACTURE LENGTH (FT)
Y=              0.0  REAL WELL Y-LOCATION (FT)
ZF=           0.0    DISTANCE FROM HORIZONTAL FRACTURE
DPENT=          0.0  DISTANCE FROM TOP OF ZONE TO TOP OF
                     PENETRATION (FT) (FT)


                       RATE          WELL RATE        CUMULATIVE TIME
                      NUMBER        (STB/DAY)         TO END OF RATE
                                                            DAYS

                        1            1714.00                0.0

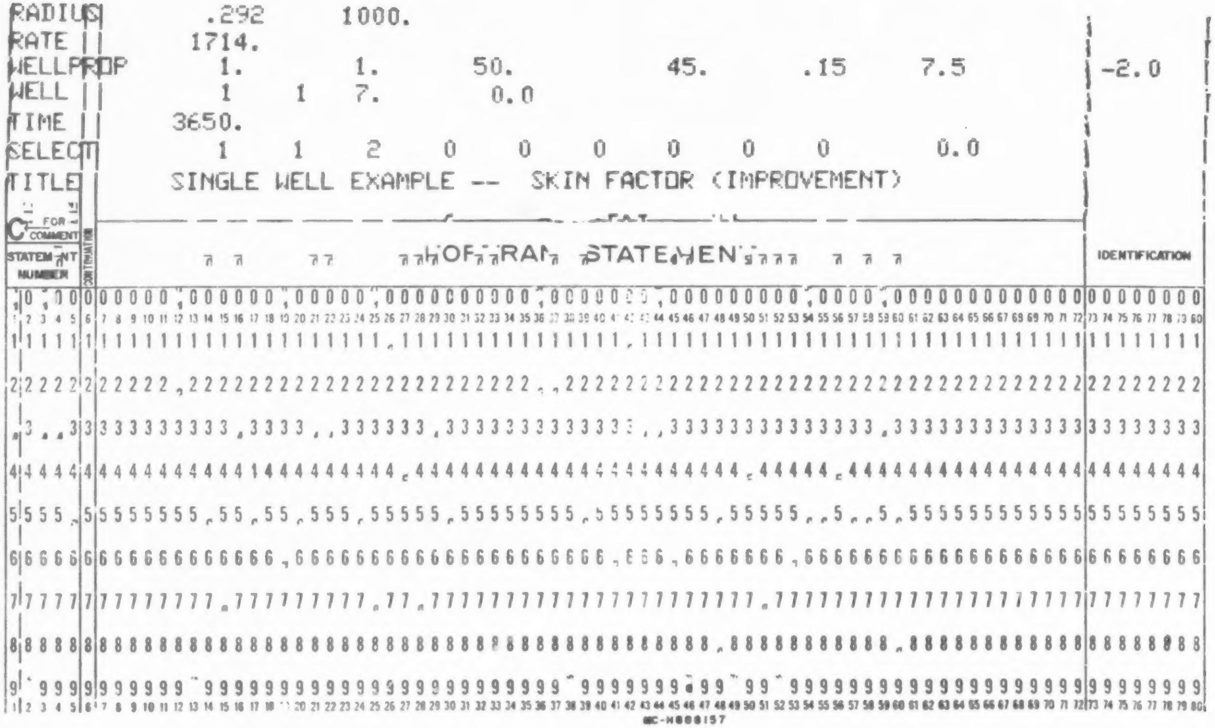

                         DISTANCE TO POINT X FOR WELL      1
                                      CHANGE IN
                         POINT        ELEVATION              RADIUS
                        NUMBER          (FT)                  (FT)

                           1             0.0                   0.29
                           2             0.0                1000.00
```

```
PRESSURE AT TIME   3650.000 (DAYS)

 POINT        RADIUS FROM         PRESSURE
NUMBER     REFERENCE WELL          (PSIA)

   1                0.292         1506.983
   2             1000.000          416.441
```



```
RADIUS       .292      1000.
RATE        1714.
WELLPROP       1.         1.        50.            45.       .15       7.5              -2.0
WELL           1     1    7.          0.0
TIME        3650.
SELECT         1     1    2     0     0     0     0     0     0          0.0
TITLE       SINGLE WELL EXAMPLE --  SKIN FACTOR (IMPROVEMENT)
```

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```
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                                        AQUIFER PRESSURE BEHAVIOR
                                          UNDER FLUID INJECTION
                                        AND/OR PRODUCTION SYSTEMS

   SINGLE WELL EXAMPLE --  SKIN FACTOR (IMPROVEMENT)



 INITIALIZATION DATA:

      NT=                1    NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
      NW=                1    NUMBER OF WELLS TO BE CONSIDERED
      NRAD=              2    NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


 AQUIFER CHARACTERISTICS TO BE CONSIDERED:

      IVIS=              0    INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
      IMAGE=             0    AQUIFER CONFINED BY BOUNDARIES?  NO
      ILEAK=             0    VERTICAL AQUIFER LEAKAGE?  NO
      IDIP=              0    DIPPING BED?  NO
      IPENT=             0    WELLS PARTIALLY PENETRATING BED?  NO
      IFRAC=             0    FRACTURE ANALYSIS?  NO
      IREF=              1    REFERENCE WELL FOR PRINTING


 GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

      CAPKT=           0.0    PERMEABILITY OF OVERLYING BED (MD)
      CAPHT=           0.0    THICKNESS OF OVERLYING BED (FT)
      CAPKB=           0.0    PERMEABILITY OF UNDERLYING BED (MD)
      CAPHB=           0.0    THICKNESS OF UNDERLYING BED (FT)
      ANGLE=           0.0    ANGLE OF BOUNDARY INTERSECTION (DEG)
      IB1=               0    BOUNDARY 1 SEALING OR LEAKING? SEAL
      IB2=               0    BOUNDARY 2 SEALING OR LEAKING? SEAL
      PI=              0.0    INTIAL RESERVOIR PRESSURE (PSI)
      DW=              0.0    DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                        RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                              INPUT DATA FOR WELL    1

TSTART=          0.0   TIME TO START OF FIRST RATE (DAYS)
PARTHK=          0.0   LENGTH OF WELL PENETRATION (FT)
PERMZ=           0.0   VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=        100.00  RADIUS EFFECTED BY SKIN (FT)
PERM=           50.00  AREAL RESERVOIR PERMEABILITY (MD)
NRATE=             1   NUMBER OF RATES
VIS=            1.000  VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=          -2.00   SKIN FACTOR AT WELLBORE
POR=            0.150  RESERVOIR POROSITY (FRACTION)
TINS=           0.0    TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=           45.00   RESERVOIR THICKNESS (FT)
VISN=           0.0    NEW FLUID VISCOSITY (CP)
BW=             1.00   FORMATION VOLUME FACTOR (RB/STB)
COMP=     0.00000750   SYSTEM COMPRESSIBILITY (1/PSI)
RW=             0.583  WELLBORE RADIUS (FT)
X=              0.0    REAL WELL X-LOCATION (FT)
XF=             0.0    FRACTURE LENGTH (FT)
Y=              0.0    REAL WELL Y-LOCATION (FT)
ZF=             0.0    DISTANCE FROM HORIZONTAL FRACTURE
DPENT=          0.0    DISTANCE FROM TOP OF ZONE TO TOP OF
                       PENETRATION (FT) (FT)


                                                 CUMULATIVE TIME
                   RATE       WELL RATE          TO END OF RATE
                  NUMBER      (STB/DAY)               DAYS

                    1          1714.00                0.0

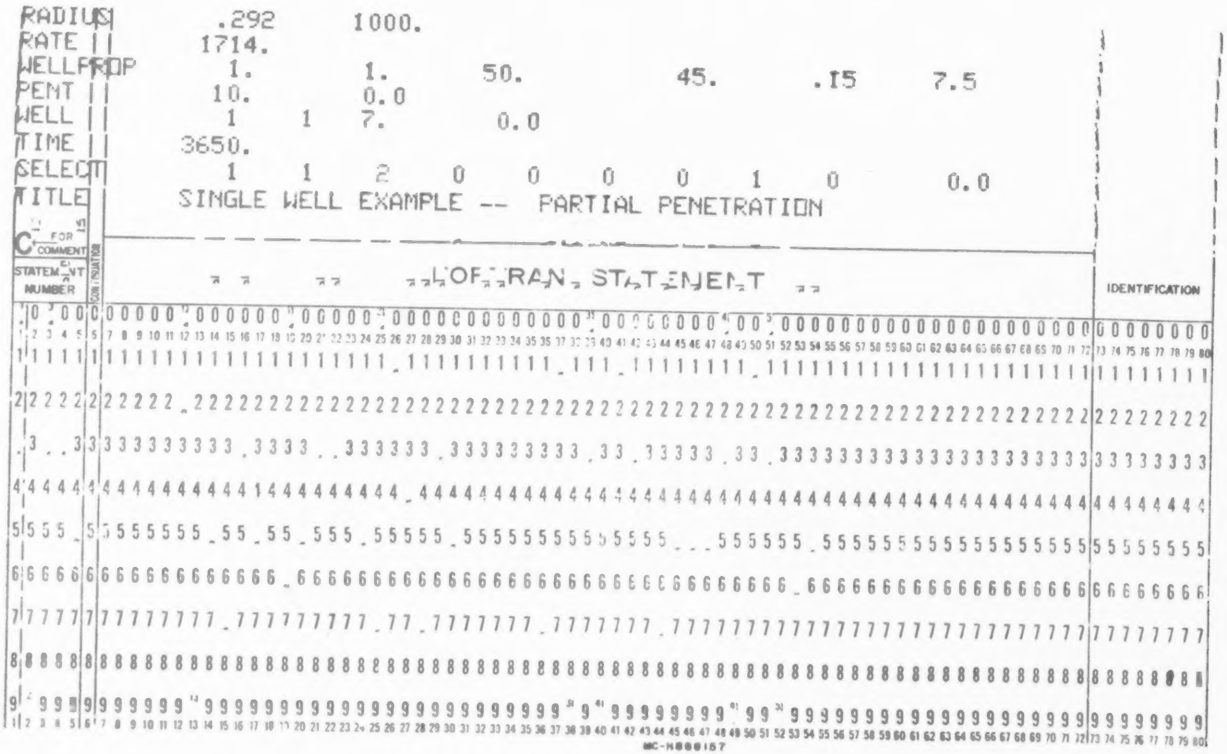

                    DISTANCE TO POINT X FOR WELL     1
                                 CHANGE IN
                    POINT        ELEVATION           RADIUS
                   NUMBER          (FT)               (FT)

                     1             0.0                0.29
                     2             0.0             1000.00
```

```
PRESSURE AT TIME   3650.000 (DAYS)

 POINT        RADIUS FROM         PRESSURE
NUMBER      REFERENCE WELL         (PSIA)

   1                 0.292        1076.731
   2              1000.000         416.441
```



```
RADIUS        .292       1000.
RATE         1714.
WELLPROP        1.          1.        50.           45.       .15      7.5
PENT           10.          0.0
WELL            1     1     7.          0.0
TIME         3650.
SELECT          1     1     2     0     0     0     0     1     0          0.0
TITLE        SINGLE WELL EXAMPLE --  PARTIAL PENETRATION
```

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```
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                                 AND/OR PRODUCTION SYSTEMS

 SINGLE WELL EXAMPLE --  PARTIAL PENETRATION


INITIALIZATION DATA:

    NT=             1   NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
    NW=             1   NUMBER OF WELLS TO BE CONSIDERED
    NRAD=           2   NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


AQUIFER CHARACTERISTICS TO BE CONSIDERED:

    IVIS=           0   INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
    IMAGE=          0   AQUIFER CONFINED BY BOUNDARIES?  NO
    ILEAK=          0   VERTICAL AQUIFER LEAKAGE?  NO
    IDIP=           0   DIPPING BED?  NO
    IPENT=          1   WELLS PARTIALLY PENETRATING BED? YES
    IFRAC=          0   FRACTURE ANALYSIS?  NO
    IREF=           1   REFERENCE WELL FOR PRINTING


GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

    CAPKT=        0.0   PERMEABILITY OF OVERLYING BED (MD)
    CAPHT=        0.0   THICKNESS OF OVERLYING BED (FT)
    CAPKB=        0.0   PERMEABILITY OF UNDERLYING BED (MD)
    CAPHB=        0.0   THICKNESS OF UNDERLYING BED (FT)
    ANGLE=        0.0   ANGLE OF BOUNDARY INTERSECTION (DEG)
    IB1=            0   BOUNDARY 1 SEALING OR LEAKING? SEAL
    IB2=            0   BOUNDARY 2 SEALING OR LEAKING? SEAL
    PI=           0.0   INTIAL RESERVOIR PRESSURE (PSI)
    DW=           0.0   DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
               RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                         INPUT DATA FOR WELL   1

TSTART=         0.0  TIME TO START OF FIRST RATE (DAYS)
PARTHK=        10.00 LENGTH OF WELL PENETRATION (FT)
PERMZ=          0.0  VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=       100.00 RADIUS EFFFCTED BY SKIN (FT)
PERM=          50.00 AREAL RESERVOIR PERMEABILITY (MD)
NRATE=             1 NUMBER OF RATES
VIS=           1.000 VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=           0.0  SKIN FACTOR AT WELLBORE
POR=           0.150 RESERVOIR POROSITY (FRACTION)
TINS=           0.0  TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=           45.00 RESERVOIR THICKNESS (FT)
VISN=          0.0   NEW FLUID VISCOSITY (CP)
BW=             1.00 FORMATION VOLUME FACTOR (RB/STB)
COMP=    0.000000750 SYSTEM COMPRESSIBILITY (1/PSI)
RW=            0.583 WELLBORE RADIUS (FT)
X=              0.0  REAL WELL X-LOCATION (FT)
XF=            0.0   FRACTURE LENGTH (FT)
Y=              0.0  REAL WELL Y-LOCATION (FT)
ZF=            0.0   DISTANCE FROM HORIZONTAL FRACTURE
DPENT=          0.0  DISTANCE FROM TOP OF ZONE TO TOP OF
                     PENETRATION (FT) (FT)


                                             CUMULATIVE TIME
                  RATE       WELL RATE       TO END OF RATE
                 NUMBER      (STB/DAY)            DAYS

                  1           1714.00             0.0

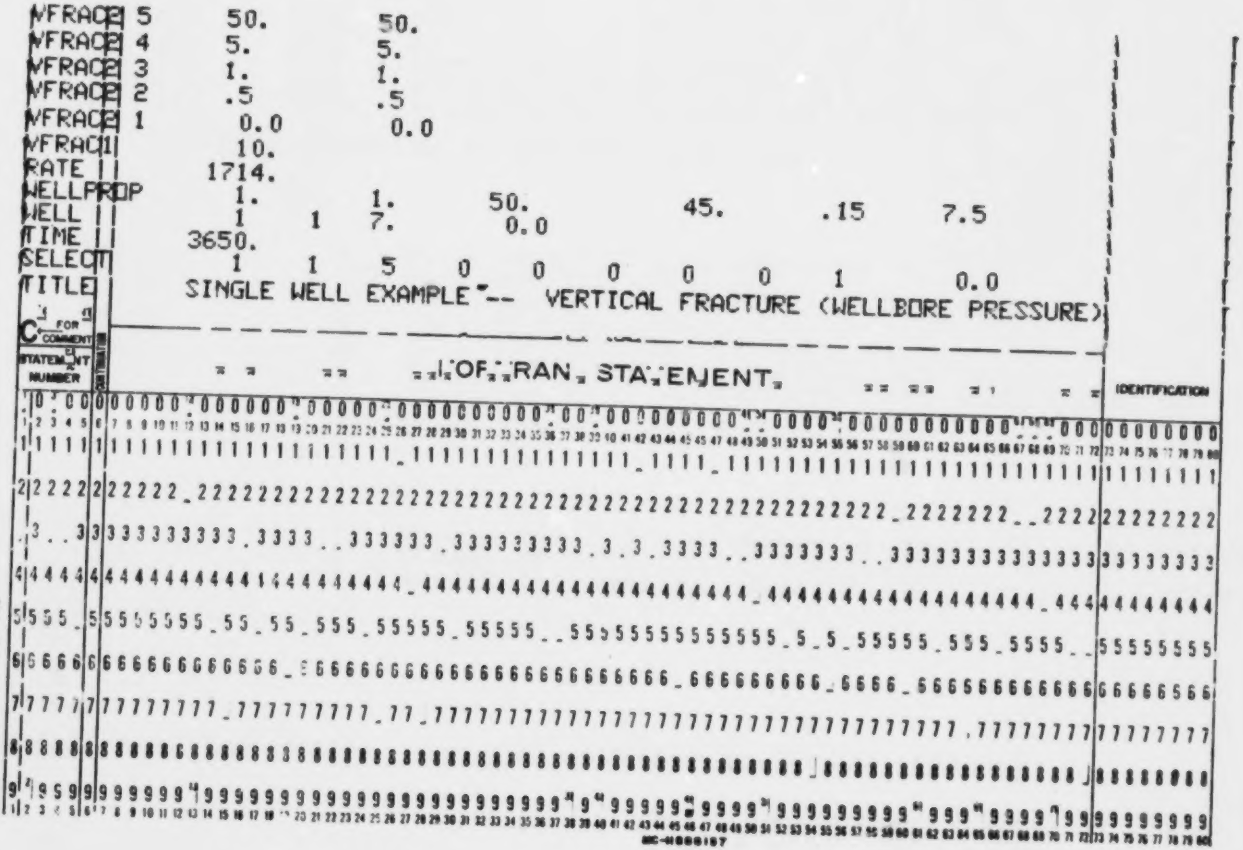

                   DISTANCE TO POINT X FOR WELL     1
                                 CHANGE IN
                   POINT         ELEVATION               RADIUS
                  NUMBER           (FT)                   (FT)

                     1              0.0                    0.29
                     2              0.0                 1000.00
```

```
PRESSURF AT TIME   3650.000 (DAYS)

 POINT        RADIUS FROM          PRESSURE
NUMBFR      REFERENCE WELL          (PSIA)

   1                 0.292         2707.638
   2              1000.000          416.441
```



```
WFRAC2 5      50.        50.
WFRAC2 4      5.         5.
WFRAC2 3      1.         1.
WFRAC2 2      .5         .5
WFRAC2 1       0.0        0.0
WFRAC1         10.
RATE         1714.
WELLPROP       1.        1.       50.                                    
WELL           1    1    7.        0.0          45.       .15      7.5
TIME        3650.
SELECT         1    1    5    0    0    0    0    0    1         0.0
TITLE       SINGLE WELL EXAMPLE --  VERTICAL FRACTURE (WELLBORE PRESSURE)
```

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```
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                                 UNDER FLUID INJECTION
                               AND/OR PRODUCTION SYSTEMS

SINGLE WELL EXAMPLE --  VERTICAL FRACTURE (WELLBORE PRESSURE)


INITIALIZATION DATA:

   NT=            1   NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
   NW=            1   NUMBER OF WELLS TO BE CONSIDERED
   NRAD=          5   NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


AQUIFER CHARACTERISTICS TO BE CONSIDERED:

   IVIS=          0   INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
   IMAGE=         0   AQUIFER CONFINED BY BOUNDARIES?  NO
   ILEAK=         0   VERTICAL AQUIFER LEAKAGE?  NO
   IDIP=          0   DIPPING BED?  NO
   IPENT=         0   WELLS PARTIALLY PENETRATING BED?  NO
   IFRAC=         1   FRACTURE ANALYSIS? YES
   IREF=          1   REFERENCE WELL FOR PRINTING


GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

   CAPKT=       0.0   PERMEABILITY OF OVERLYING BED (MD)
   CAPHT=       0.0   THICKNESS OF OVERLYING BED (FT)
   CAPKB=       0.0   PERMEABILITY OF UNDERLYING BED (MD)
   CAPHB=       0.0   THICKNESS OF UNDERLYING BED (FT)
   ANGLE=       0.0   ANGLE OF BOUNDARY INTERSECTION (DEG)
   IB1=           0   BOUNDARY 1 SEALING OR LEAKING? SEAL
   IB2=           0   BOUNDARY 2 SEALING OR LEAKING? SEAL
   PI=          0.0   INTIAL RESERVOIR PRESSURE (PSI)
   DW=          0.0   DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                    RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                          INPUT DATA FOR WELL     1

TSTART=         0.0  TIME TO START OF FIRST RATE (DAYS)
PARTHK=         0.0  LENGTH OF WELL PENETRATION (FT)
PERMZ=          0.0  VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=      100.00  RADIUS EFFECTED BY SKIN (FT)
PERM=         50.00  AREAL RESERVOIR PERMEABILITY (MD)
NRATE=            1  NUMBER OF RATES
VIS=          1.000  VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=         0.0    SKIN FACTOR AT WELLBORE
POR=          0.150  RESERVOIR POROSITY (FRACTION)
TINS=           0.0  TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=          45.00  RESERVOIR THICKNESS (FT)
VISN=         0.0    NEW FLUID VISCOSITY (CP)
BW=            1.00  FORMATION VOLUME FACTOR (RB/STB)
COMP=    0.00000750  SYSTEM COMPRESSIBILITY (1/PSI)
RW=           0.583  WELLBORE RADIUS (FT)
X=              0.0  REAL WELL X-LOCATION (FT)
XF=          10.000  FRACTURE LENGTH (FT)
Y=              0.0  REAL WELL Y-LOCATION (FT)
ZF=           0.0    DISTANCE FROM HORIZONTAL FRACTURE
DPENT=          0.0  DISTANCE FROM TOP OF ZONE TO TOP OF
                     PENETRATION (FT) (FT)


                                                        CUMULATIVE TIME
                        RATE        WELL RATE           TO END OF RATE
                       NUMBER       (STB/DAY)                DAYS

                          1          1714.00                  0.0


                         DISTANCE TO POINT X FOR WELL     1
                                CHANGE IN
                POINT           ELEVATION              X-LOCATION            Y-LOCATION
               NUMBER             (FT)                    (FT)                  (FT)

                  1               0.0                     0.0                   0.0
                  2               0.0                     0.50                  0.50
                  3               0.0                     1.00                  1.00
                  4               0.0                     5.00                  5.00
                  5               0.0                    50.00                 50.00
```

```
PRESSURE AT TIME   3650.000 (DAYS)

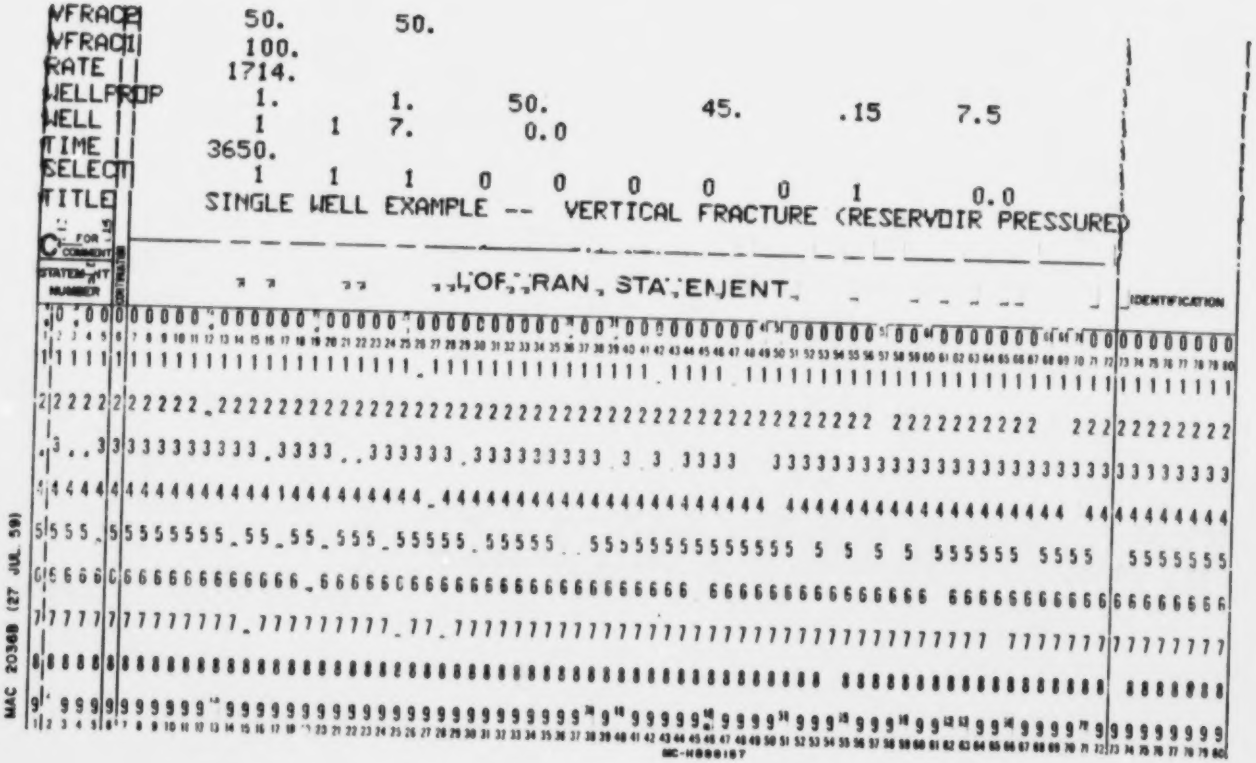
 RADIUS POINT NUMBER=   1
 WELL NUMBER             PRESSURE (PSIA)
      1                    1019.39

 RADIUS POINT NUMBER=   2
 WELL NUMBER             PRESSURE (PSIA)
      1                    1019.12

 RADIUS POINT NUMBER=   3
 WELL NUMBER             PRESSURE (PSIA)
      1                    1018.31

 RADIUS POINT NUMBER=   4
 WELL NUMBER             PRESSURE (PSIA)
      1                     991.75

 RADIUS POINT NUMBER=   5
 WELL NUMBER             PRESSURE (PSIA)
      1                     701.42
```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```
VFRAC2       50.         50.
VFRAC1       100.
RATE        1714.
WELLPROP      1.          1.        50.            45.       .15     7.5
WELL          1     1     7.         0.0
TIME        3650.
SELECT        1     1     1     0     0     0     0     0     1         0.0
TITLE       SINGLE WELL EXAMPLE --  VERTICAL FRACTURE (RESERVOIR PRESSURE)
```

```
                                        DETERMINATION OF
                                    AQUIFER PRESSURE BEHAVIOR
                                      UNDER FLUID INJECTION
                                    AND/OR PRODUCTION SYSTEMS

SINGLE WELL EXAMPLE --  VERTICAL FRACTURE (RESERVOIR PRESSURE)


INITIALIZATION DATA:

    NT=              1   NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
    NW=              1   NUMBER OF WELLS TO BE CONSIDERED
    NRAD=            1   NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


AQUIFER CHARACTERISTICS TO BE CONSIDERED:

    IVIS=            0   INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
    IMAGE=           0   AQUIFER CONFINED BY BOUNDARIES?  NO
    ILEAK=           0   VERTICAL AQUIFER LEAKAGE?  NO
    IDIP=            0   DIPPING BED?  NO
    IPENT=           0   WELLS PARTIALLY PENETRATING BED?  NO
    IFRAC=           1   FRACTURE ANALYSIS? YES
    IREF=            1   REFERENCE WELL FOR PRINTING


GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

    CAPKT=        0.0    PERMEABILITY OF OVERLYING BED (MD)
    CAPHT=        0.0    THICKNESS OF OVERLYING BED (FT)
    CAPKB=        0.0    PERMEABILITY OF UNDERLYING BED (MD)
    CAPHB=        0.0    THICKNESS OF UNDERLYING BED (FT)
    ANGLE=        0.0    ANGLE OF BOUNDARY INTERSECTION (DEG)
    IB1=            0    BOUNDARY 1 SEALING OR LEAKING? SEAL
    IB2=            0    BOUNDARY 2 SEALING OR LEAKING? SEAL
    PI=           0.0    INTIAL RESERVOIR PRESSURE (PSI)
    DW=           0.0    DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                    RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                          INPUT DATA FOR WELL    1

TSTARI=          0.0  TIME TO START OF FIRST RATE (DAYS)
PARTHK=          0.0  LENGTH OF WELL PENETRATION (FT)
PERMZ=           0.0  VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=       100.00  RADIUS EFFECTED BY SKIN (FT)
PERM=          50.00  AREAL RESERVOIR PERMEABILITY (MD)
NRATE=             1  NUMBER OF RATES
VIS=           1.000  VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=            0.0  SKIN FACTOR AT WELLBORE
POR=           0.150  RESERVOIR POROSITY (FRACTION)
TINS=            0.0  TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=           45.00  RESERVOIR THICKNESS (FT)
VISN=          0.0    NEW FLUID VISCOSITY (CP)
BW=             1.00  FORMATION VOLUME FACTOR (RB/STB)
COMP=     0.00000750  SYSTEM COMPRESSIBILITY (1/PSI)
RW=            0.583  WELLBORE RADIUS (FT)
X=               0.0  REAL WELL X-LOCATION (FT)
XF=          100.000  FRACTURE LENGTH (FT)
Y=               0.0  REAL WELL Y-LOCATION (FT)
ZF=            0.0    DISTANCE FROM HORIZONTAL FRACTURE
DPENT=           0.0  DISTANCE FROM TOP OF ZONE TO TOP OF
                      PENETRATION (FT) (FT)


                                              CUMULATIVE TIME
                     RATE        WELL RATE    TO END OF RATE
                    NUMBER       (STB/DAY)         DAYS

                      1           1714.00          0.0

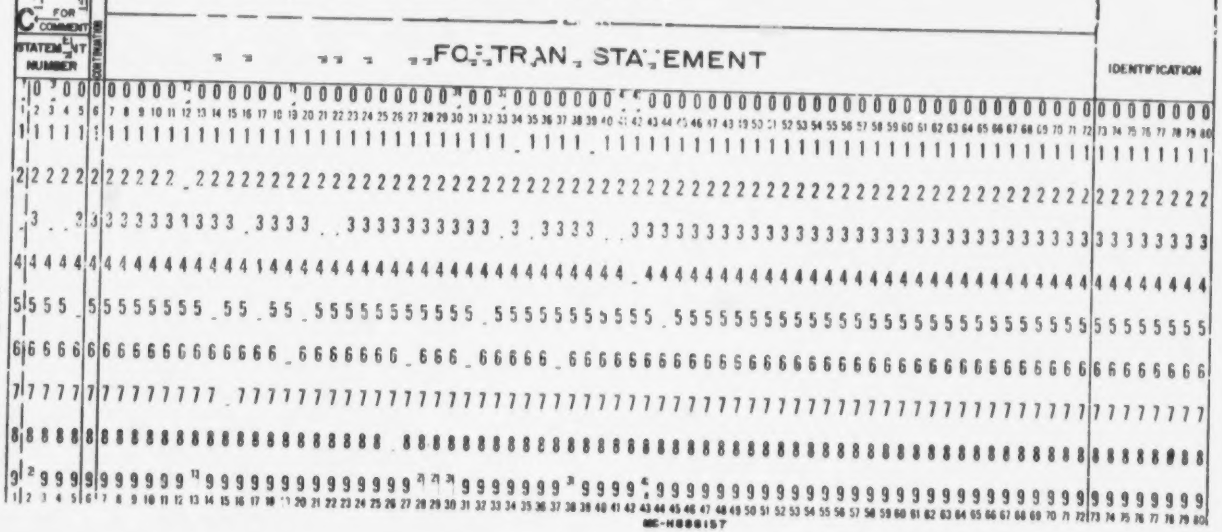

                        DISTANCE TO POINT X FOR WELL    1
                            CHANGE IN
             POINT          ELEVATION           X-LOCATION             Y-LOCATION
            NUMBER            (FT)                 (FT)                   (FT)

               1               0.0                50.00                  50.00
```

```
PRESSURE AT TIME   3650.000 (DAYS)

 RADIUS POINT NUMBER=   1
 WELL NUMBER                PRESSURE (PSIA)
       1                       744.07
```

```
RADIUS      50.       300.      600.
HFRAC      100.        100.       25.
RATE      5000.
WELLPROP     1.        1.       100.       50.       .25       7.5
WELL         1    1               0.0
TIME      1000.
SELECT       1    1    3    0    0    0    0    0    2         0.0
TITLE     SINGLE WELL - HORIZONTAL FRACTURE
```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```
                              DETERMINATION OF
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                            UNDER FLUID INJECTION
                          AND/OR PRODUCTION SYSTEMS

 SINGLE WELL - HORIZONTAL FRACTURE


INITIALIZATION DATA:

     NT=           1   NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
     NW=           1   NUMBER OF WELLS TO BE CONSIDERED
     NRAD=         3   NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


AQUIFER CHARACTERISTICS TO BE CONSIDERED:

     IVIS=         0   INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
     IMAGE=        0   AQUIFER CONFINED BY BOUNDARIES?  NO
     ILEAK=        0   VERTICAL AQUIFER LEAKAGE?  NO
     IDIP=         0   DIPPING BED?  NO
     IPENT=        0   WELLS PARTIALLY PENETRATING BED?  NO
     IFRAC=        2   FRACTURE ANALYSIS? YES
     IREF=         1   REFERENCE WELL FOR PRINTING


GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

     CAPKT=      0.0   PERMEABILITY OF OVERLYING BED (MD)
     CAPHT=      0.0   THICKNESS OF OVERLYING BED (FT)
     CAPKB=      0.0   PERMEABILITY OF UNDERLYING BED (MD)
     CAPHB=      0.0   THICKNESS CF UNDERLYING BED (FT)
     ANGLE=      0.0   ANGLE OF BOUNDARY INTERSECTION (DEG)
     IB1=          0   BOUNDARY 1 SEALING OR LEAKING? SEAL
     IB2=          0   BOUNDARY 2 SEALING OR LEAKING? SEAL
     PI=         0.0   INTIAL RESERVOIR PRESSURE (PSI)
     DW=         0.0   DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                                  RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                                         INPUT DATA FOR WELL    1

TSTART=          0.0   TIME TO START OF FIRST RATE (DAYS)
PARTHK=          0.0   LENGTH OF WELL PENETRATION (FT)
PERMZ=         100.00  VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=        100.00  RADIUS EFFECTED BY SKIN (FT)
PERM=          100.00  AREAL RESERVOIR PERMEABILITY (MD)
NRATE=             1   NUMBER OF RATES
VIS=           1.000   VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=            0.0   SKIN FACTOR AT WELLBORE
POR=           0.250   RESERVOIR POROSITY (FRACTION)
TINS=            0.0   TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=           50.00   RESERVOIR THICKNESS (FT)
VISN=            0.0   NEW FLUID VISCOSITY (CP)
BW=             1.00   FORMATION VOLUME FACTOR (RB/STB)
COMP=     0.00000750   SYSTEM COMPRESSIBILITY (1/PSI)
RW=            0.250   WELLBORE RADIUS (FT)
X=               0.0   REAL WELL X-LOCATION (FT)
XF=          100.000   FRACTURE LENGTH (FT)
Y=               0.0   REAL WELL Y-LOCATION (FT)
ZF=           25.000   DISTANCE FROM HORIZONTAL FRACTURE
DPENT=           0.0   DISTANCE FROM TOP OF ZONE TO TOP OF
                       PENETRATION (FT) (FT)


                         RATE           WELL RATE          CUMULATIVE TIME
                        NUMBER         (STB/DAY)           TO END OF RATE
                                                                DAYS

                          1             5000.00                  0.0


                            DISTANCE TO POINT X FOR WELL      1
                                          CHANGE IN
                           POINT          ELEVATION                 RADIUS
                          NUMBER            (FT)                     (FT)

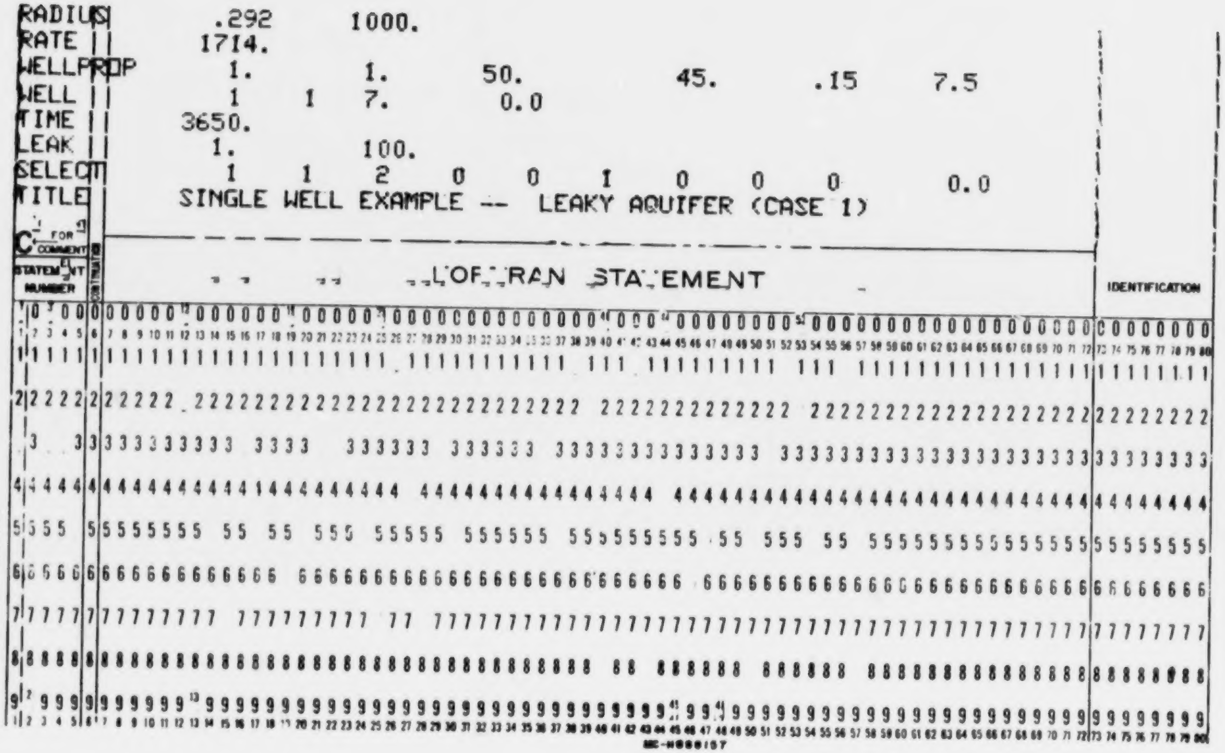
                             1               0.0                     50.00
                             2               0.0                    300.00
                             3               0.0                    600.00
```

```
          PRESSURE AT TIME   1000.000 (DAYS)

           RADIUS POINT NUMBER=   1
           WELL NUMBER              PRESSURE (PSIA)
PROXIMATIONS FOR HORIZONTAL FRACTURE FAIL DUE TO RADIUS LIMITATIONS FOR WELL    1 RADIUS=     50.00
                     1                   1541.36

           RADIUS POINT NUMBER=   2
           WELL NUMBER              PRESSURE (PSIA)
                     1                    638.17

           RADIUS POINT NUMBER=   3
           WELL NUMBER              PRESSURE (PSIA)
                     1                    540.30
```



```
RADIUS       .292      1000.
RATE        1714.
WELLPROP      1.         1.       50.            45.       .15      7.5
WELL          1     1    7.        0.0
TIME        3650.
LEAK          1.        100.
SELECT        1     1    2     0     0     1     0     0     0          0.0
TITLE       SINGLE WELL EXAMPLE --  LEAKY AQUIFER (CASE 1)
```

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```
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                                          AQUIFER PRESSURE BEHAVIOR
                                            UNDER FLUID INJECTION
                                          AND/OR PRODUCTION SYSTEMS

 SINGLE WELL EXAMPLF --  LEAKY AQUIFER (CASE 1)


INITIALIZATION DATA:

    NT=            1   NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
    NW=            1   NUMBER OF WELLS TO BE CONSIDERED
    NRAD=          2   NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


AQUIFER CHARACTERISTICS TO BE CONSIDERED:

    IVIS=          0   INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
    IMAGE=         0   AQUIFER CONFINED BY BOUNDARIES?  NO
    ILEAK=         1   VERTICAL AQUIFER LEAKAGE? YES
    IDIP=          0   DIPPING BED?  NO
    IPENT=         0   WELLS PARTIALLY PENETRATING BED?  NO
    IFRAC=         0   FRACTURE ANALYSIS?  NO
    IREF=          1   REFERENCE WELL FOR PRINTING


GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

    CAPKT=      1.000  PERMEABILITY OF OVERLYING BED (MD)
    CAPHT=    100.00   THICKNESS OF OVERLYING BED (FT)
    CAPKB=      0.0    PERMEABILITY OF UNDERLYING BED (MD)
    CAPHB=      0.0    THICKNESS OF UNDERLYING BED (FT)
    ANGLE=      0.0    ANGLE OF BOUNDARY INTERSECTION (DEG)
    IB1=          0    BOUNDARY 1 SEALING OR LEAKING? SEAL
    IB2=          0    BOUNDARY 2 SEALING OR LEAKING? SEAL
    PI=         0.0    INTIAL RESERVOIR PRESSURE (PSI)
    DW=         0.0    DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                    RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                            INPUT DATA FOR WELL    1

TSTART=           0.0  TIME TO START OF FIRST RATE (DAYS)
PARTHK=           0.0  LENGTH OF WELL PENETRATION (FT)
PERMZ=            0.0  VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=        100.00  RADIUS EFFECTED BY SKIN (FT)
PERM=           50.00  AREAL RESERVOIR PERMEABILITY (MD)
NRATE=              1  NUMBER OF RATES
VIS=            1.000  VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=             0.0  SKIN FACTOR AT WELLBORE
POR=            0.150  RESERVOIR POROSITY (FRACTION)
TINS=             0.0  TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=            45.00  RESERVOIR THICKNESS (FT)
VISN=             0.0  NEW FLUID VISCOSITY (CP)
BW=              1.00  FORMATION VOLUME FACTOR (RB/STB)
COMP=      0.00000750  SYSTEM COMPRESSIBILITY (1/PSI)
RW=             0.583  WELLBORE RADIUS (FT)
X=                0.0  REAL WELL X-LOCATION (FT)
XF=             0.0    FRACTURE LENGTH (FT)
Y=                0.0  REAL WELL Y-LOCATION (FT)
ZF=             0.0    DISTANCE FROM HORIZONTAL FRACTURE
DPENT=            0.0  DISTANCE FROM TOP OF ZONE TO TOP OF
                       PENETRATION (FT) (FT)


                                                CUMULATIVE TIME
                     RATE          WELL RATE     TO END OF RATE
                    NUMBER         (STB/DAY)          DAYS

                     1             1714.00            0.0

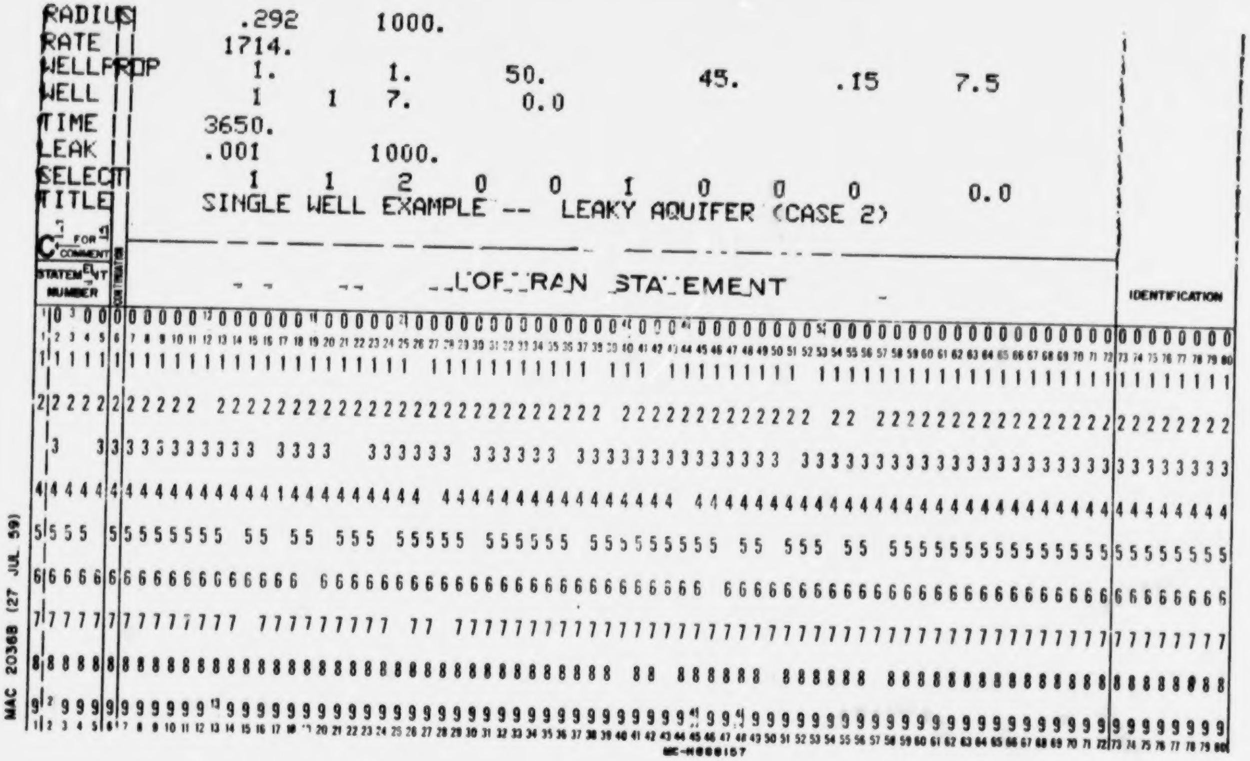

                      DISTANCE TO POINT X FOR WELL     1
                                   CHANGE IN
                      POINT        ELEVATION            RADIUS
                     NUMBER          (FT)                (FT)

                        1            0.0                  0.29
                        2            0.0               1000.00
```

```
   PRESSURE AT TIME   3650.000 (DAYS)

  POINT          RADIUS FROM          PRESSURE
 NUMBER        REFERENCE WELL          (PSIA)

    1                   0.292          807.695
    2                1000.000            2.600
```



```
RADIUS      .292     1000.
RATE       1714.
WELLPROP      1.        1.       50.            45.      .15     7.5
WELL          1    1    7.         0.0
TIME       3650.
LEAK       .001       1000.
SELECT        1    1    2    0    0    1    0    0    0         0.0
TITLE      SINGLE WELL EXAMPLE --  LEAKY AQUIFER (CASE 2)
```

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```
                                      DETERMINATION OF
                                   AQUIFER PRESSURE BEHAVIOR
                                     UNDER FLUID INJECTION
                                   AND/OR PRODUCTION SYSTEMS

  SINGLE WELL EXAMPLE --  LEAKY AQUIFER (CASE 2)


 INITIALIZATION DATA:

     NT=              1   NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
     NW=              1   NUMBER OF WELLS TO BE CONSIDERED
     NRAD=            2   NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


 AQUIFER CHARACTERISTICS TO BE CONSIDERED:

     IVIS=            0   INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
     IMAGE=           0   AQUIFER CONFINED BY BOUNDARIES?  NO
     ILEAK=           1   VERTICAL AQUIFER LEAKAGE? YES
     IDIP=            0   DIPPING BED?  NO
     IPENT=           0   WELLS PARTIALLY PENETRATING BED?  NO
     IFRAC=           0   FRACTURE ANALYSIS?  NO
     IREF=            1   REFEPENCE WELL FOR PRINTING


 GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

     CAPKT=       0.001   PERMEABILITY OF OVERLYING BED (MD)
     CAPHT=     1000.00   THICKNESS OF OVERLYING BED (FT)
     CAPKB=         0.0   PERMEABILITY OF UNDERLYING BED (MD)
     CAPHB=         0.0   THICKNESS OF UNDERLYING BED (FT)
     ANGLE=         0.0   ANGLE OF BOUNDARY INTERSECTION (DEG)
     IB1=             0   BOUNDARY 1 SEALING OR LEAKING? SEAL
     IB2=             0   BOUNDARY 2 SEALING OR LEAKING? SEAL
     PI=            0.0   INTIAL RESERVOIR PRESSURE (PSI)
     DW=            0.0   DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                    RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                            INPUT DATA FOR WELL    1

TSTART=          0.0  TIME TO START OF FIRST RATE (DAYS)
PARTHK=          0.0  LENGTH OF WELL PENETRATION (FT)
PERMZ=           0.0  VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=       100.00  RADIUS EFFECTED BY SKIN (FT)
PERM=          50.00  AREAL RESERVOIR PERMEABILITY (MD)
NRATE=             1  NUMBER OF RATES
VIS=           1.000  VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=            0.0  SKIN FACTOR AT WELLBORE
POR=           0.150  RESERVOIR POROSITY (FRACTION)
TINS=            0.0  TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=           45.00  RESERVOIR THICKNESS (FT)
VISN=          0.0    NEW FLUID VISCOSITY (CP)
BW=             1.00  FORMATION VOLUME FACTOR (RB/STB)
COMP=     0.00000750  SYSTEM COMPRESSIBILITY (1/PSI)
RW=            0.583  WELLBORE RADIUS (FT)
X=               0.0  REAL WELL X-LOCATION (FT)
XF=            0.0    FRACTURE LENGTH (FT)
Y=               0.0  REAL WELL Y-LOCATION (FT)
ZF=            0.0    DISTANCE FROM HORIZONTAL FRACTURE
DPENT=           0.0  DISTANCE FROM TOP OF ZONE TO TOP OF
                      PENETRATION (FT) (FT)


                                                      CUMULATIVE TIME
                     RATE          WELL RATE          TO END OF RATE
                    NUMBER        (STB/DAY)                DAYS

                     1             1714.00                 0.0

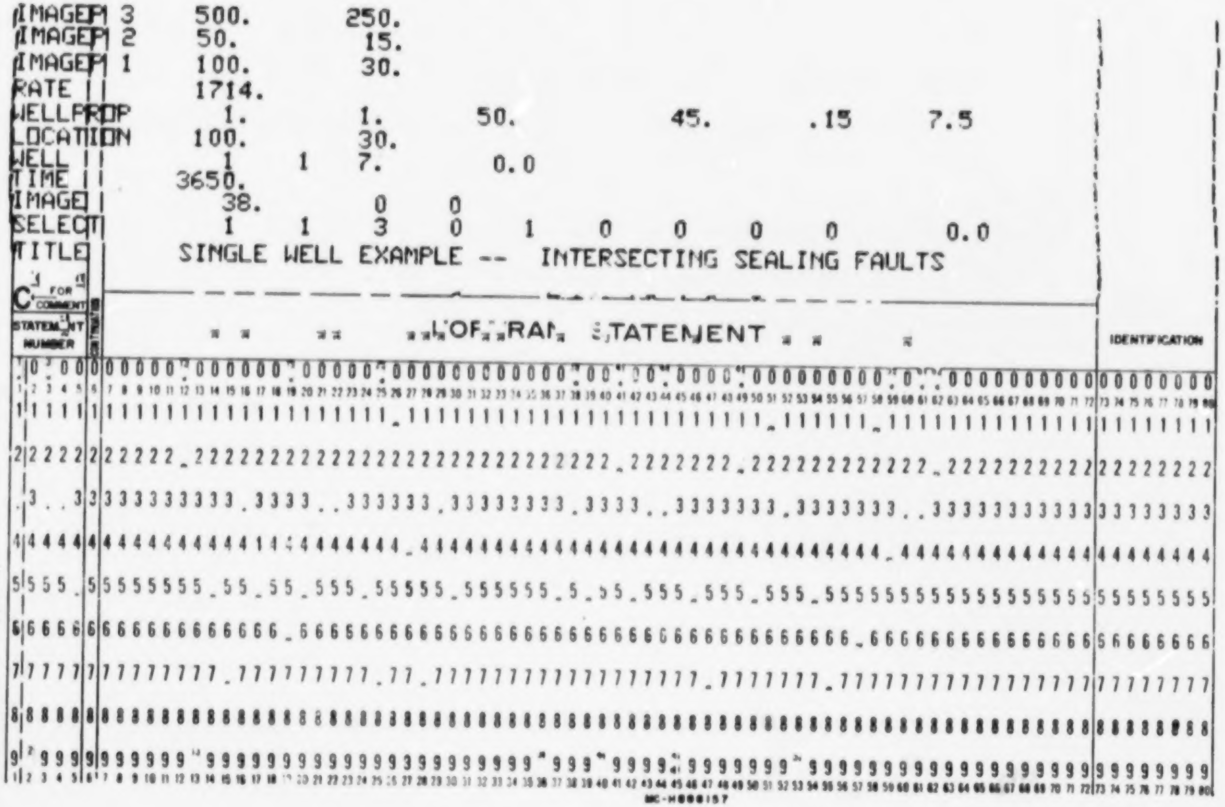

                        DISTANCE TO POINT X FOR WELL     1
                                     CHANGE IN
                      POINT          ELEVATION               RADIUS
                      NUMBER           (FT)                   (FT)

                        1               0.0                    0.29
                        2               0.0                 1000.00
```

```
 PRESSURE AT TIME   3650.000 (DAYS)

 POINT        RADIUS FROM        PRESSURE
NUMBER     REFERENCE WELL         (PSIA)

   1                0.292        1269.900
   2             1000.000         394.516
```



```
IMAGEP 3     500.        250.
IMAGEP 2     50.          15.
IMAGEP 1     100.         30.
RATE         1714.
WELLPROP       1.         1.       50.             45.       .15      7.5
LOCATION     100.         30.
WELL           1     1    7.        0.0
TIME        3650.
IMAGE           38.        0    0
SELECT          1    1    3    0    1    0    0    0    0         0.0
TITLE       SINGLE WELL EXAMPLE --  INTERSECTING SEALING FAULTS
```

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```
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                                     AQUIFER PRESSURE BEHAVIOR
                                       UNDER FLUID INJECTION
                                     AND/OR PRODUCTION SYSTEMS

   SINGLE WELL EXAMPLE --  INTERSECTING SEALING FAULTS


  INITIALIZATION DATA:

       NT=              1    NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
       NW=              1    NUMBER OF WELLS TO BE CONSIDERED
       NRAD=            3    NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


  AQUIFER CHARACTERISTICS TO BE CONSIDERED:

       IVIS=            0    INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
       IMAGE=           1    AQUIFER CONFINED BY BOUNDARIES? YES
       ILEAK=           0    VERTICAL AQUIFER LEAKAGE?  NO
       IDIP=            0    DIPPING BED?  NO
       IPENT=           0    WELLS PARTIALLY PENETRATING BED?  NO
       IFRAC=           0    FRACTURE ANALYSIS?  NO
       IREF=            1    REFERENCE WELL FOR PRINTING


  GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

       CAPKT=         0.0    PERMEABILITY OF OVERLYING BED (MD)
       CAPHT=         0.0    THICKNESS OF OVERLYING BED (FT)
       CAPKB=         0.0    PERMEABILITY OF UNDERLYING BED (MD)
       CAPHB=         0.0    THICKNESS OF UNDERLYING BED (FT)
       ANGLE=       38.00    ANGLE OF BOUNDARY INTERSECTION (DEG)
       IB1=             0    BOUNDARY 1 SEALING OR LEAKING? SEAL
       IB2=             0    BOUNDARY 2 SEALING OR LEAKING? SEAL
       PI=            0.0    INTIAL RESERVOIR PRESSURE (PSI)
       DW=            0.0    DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                        RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                               INPUT DATA FOR WELL    1

TSTART=       0.0   TIME TO START OF FIRST RATE (DAYS)
PARTHK=       0.0   LENGTH OF WELL PENETRATION (FT)
PERMZ=        0.0   VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=     100.00  RADIUS EFFECTED BY SKIN (FT)
PERM=        50.00  AREAL RESERVOIR PERMEABILITY (MD)
NRATE=          1   NUMBER OF RATES
VIS=         1.000  VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=         0.0   SKIN FACTOR AT WELLBORE
POR=         0.150  RESERVOIR POROSITY (FRACTION)
TINS=         0.0   TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=         45.00  RESERVOIR THICKNESS (FT)
VISN=         0.0   NEW FLUID VISCOSITY (CP)
BW=           1.00  FORMATION VOLUME FACTOR (RB/STB)
COMP=   0.00000750  SYSTEM COMPRESSIBILITY (1/PSI)
RW=          0.583  WELLBORE RADIUS (FT)
X=          100.00  REAL WELL X-LOCATION (FT)
XF=          0.0    FRACTURE LENGTH (FT)
Y=           30.00  REAL WELL Y-LOCATION (FT)
ZF=          0.0    DISTANCE FROM HORIZONTAL FRACTURE
DPENT=        0.0   DISTANCE FROM TOP OF ZONE TO TOP OF
                    PENETRATION (FT) (FT)


                       RATE        WELL RATE        CUMULATIVE TIME
                      NUMBER      (STB/DAY)         TO END OF RATE
                                                        DAYS

                        1          1714.00               0.0

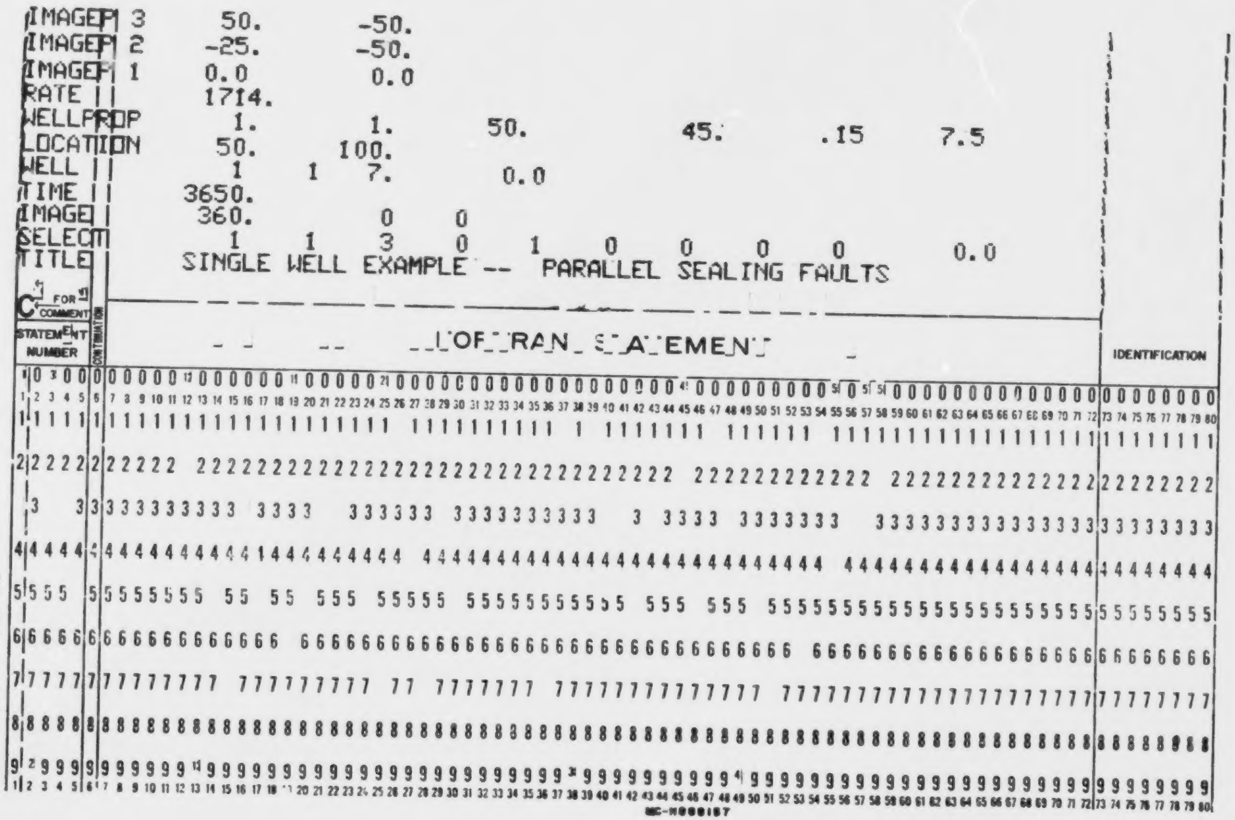

                         DISTANCE TO POINT X FOR WELL    1
                           CHANGE IN
               POINT       ELEVATION           X-LOCATION            Y-LOCATION
              NUMBER          (FT)                (FT)                  (FT)

                 1             0.0               100.00                 30.00
                 2             0.0                50.00                 15.00
                 3             0.0               500.00                250.00
```

```
  PRESSURE AT TIME   3650.000 (DAYS)

  POINT          RADIUS FROM         PRESSURE
 NUMBER       REFERENCE WELL          (PSIA)

   1                   0.583        8184.102
   2                  52.202        6272.133
   3                 456.509        4432.625
```



```
IMAGEP 3      50.        -50.
IMAGEP 2     -25.        -50.
IMAGEP 1     0.0          0.0
RATE          1714.
WELLPROP        1.         1.        50.          45.        .15     7.5
LOCATION      50.       100.
WELL            1     1    7.         0.0
TIME         3650.
IMAGE         360.          0     0
SELECT          1     1     3     0     1     0     0     0     0          0.0
TITLE        SINGLE WELL EXAMPLE --  PARALLEL SEALING FAULTS
```

C FOR COMMENT

STATEMENT NUMBER

FORTRAN STATEMENT

IDENTIFICATION

MAC 20368 (27 JUL 59)

```
                                     DETERMINATION OF
                                 AQUIFER PRESSURE BEHAVIOR
                                   UNDER FLUID INJECTION
                                 AND/OR PRODUCTION SYSTEMS

  SINGLE WELL EXAMPLE --  PARALLEL SEALING FAULTS


 INITIALIZATION DATA:

    NT=             1   NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED
    NW=             1   NUMBER OF WELLS TO BE CONSIDERED
    NRAD=           3   NUMBER OF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


 AQUIFER CHARACTERISTICS TO BE CONSIDERED:

    IVIS=           0   INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
    IMAGE=          1   AQUIFER CONFINED BY BOUNDARIES? YES
    ILEAK=          0   VERTICAL AQUIFER LEAKAGE?  NO
    IDIP=           0   DIPPING BED?  NO
    IPENT=          0   WELLS PARTIALLY PENETRATING BED?  NO
    IFRAC=          0   FRACTURE ANALYSIS?  NO
    IREF=           1   REFERENCE WELL FOR PRINTING


 GENERAL DATA CORRESPONDING TO OPTIONS SELECTED:

    CAPKT=        0.0   PERMEABILITY OF OVERLYING BED (MD)
    CAPHT=        0.0   THICKNESS OF OVERLYING BED (FT)
    CAPKB=        0.0   PERMEABILITY OF UNDERLYING BED (MD)
    CAPHB=        0.0   THICKNESS OF UNDERLYING BED (FT)
    ANGLE=     360.00   ANGLE OF BOUNDARY INTERSECTION (DEG)
    IB1=            0   BOUNDARY 1 SEALING OR LEAKING? SEAL
    IB2=            0   BOUNDARY 2 SEALING OR LEAKING? SEAL
    PI=           0.0   INTIAL RESERVOIR PRESSURE (PSI)
    DW=           0.0   DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                        RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                              INPUT DATA FOR WELL    1

TSTART=        0.0   TIME TO START OF FIRST RATE (DAYS)
PARTHK=        0.0   LENGTH OF WELL PENETRATION (FT)
PERMZ=         0.0   VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=      100.00  RADIUS EFFECTED BY SKIN (FT)
PERM=         50.00  AREAL RESERVOIR PERMEABILITY (MD)
NRATE=          1    NUMBER OF RATES
VIS=          1.000  VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=         0.0    SKIN FACTOR AT WELLBORE
POR=          0.150  RESERVOIR POROSITY (FRACTION)
TINS=         0.0    TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=         45.00   RESERVOIR THICKNESS (FT)
VISN=         0.0    NEW FLUID VISCOSITY (CP)
BW=           1.00   FORMATION VOLUME FACTOR (RB/STB)
COMP=   0.00000750   SYSTEM COMPRESSIBILITY (1/PSI)
RW=           0.583  WELLBORE RADIUS (FT)
X=           50.00   REAL WELL X-LOCATION (FT)
XF=           0.0    FRACTURE LENGTH (FT)
Y=          100.00   REAL WELL Y-LOCATION (FT)
ZF=           0.0    DISTANCE FROM HORIZONTAL FRACTURE
DPENT=        0.0    DISTANCE FROM TOP OF ZONE TO TOP OF
                     PENETRATION (FT) (FT)


                                                      CUMULATIVE TIME
                       RATE          WELL RATE        TO END OF RATE
                      NUMBER        (STB/DAY)             DAYS

                        1            1714.00               0.0

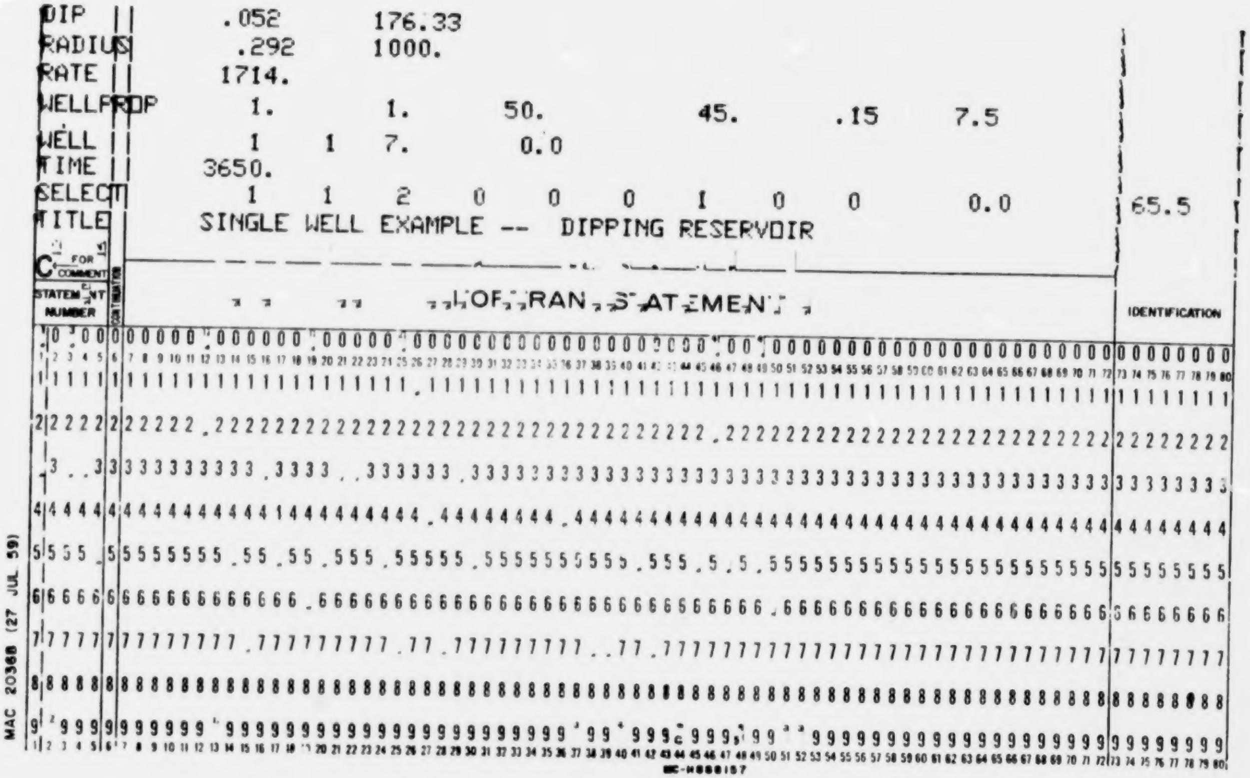

                         DISTANCE TO POINT X FOR WELL    1
                                 CHANGE IN
              POINT              ELEVATION          X-LOCATION          Y-LOCATION
              NUMBER               (FT)                (FT)                (FT)

                1                  0.0                  0.0                 0.0
                2                  0.0                -25.00              -50.00
                3                  0.0                 50.00              -50.00
```

```
   PRESSURE AT TIME   3650.000 (DAYS)

  POINT        RADIUS FROM         PRESSURE
 NUMBER      REFERENCE WELL         (PSIA)

   1                  0.583       5196.781
   2                 55.902       4202.145
   3                 70.711       4174.375
```



```
DIP         .052      176.33
RADIUS       .292     1000.
RATE        1714.
WELLPROP      1.        1.      50.             45.      .15      7.5
WELL          1    1    7.       0.0
TIME       3650.
SELECT        1    1    2    0    0    0    1    0    0       0.0       65.5
TITLE      SINGLE WELL EXAMPLE --  DIPPING RESERVOIR
```

C FOR COMMENT
STATEMENT NUMBER
CONTINUATION
FORTRAN STATEMENT
IDENTIFICATION
MAC 2036B (27 JUL 59)

```
                                   DETERMINATION OF
                               AQUIFER PRESSURE BEHAVIOR
                                 UNDER FLUID INJECTION
                               AND/OR PRODUCTION SYSTEMS

SINGLF WELL EXAMPLE --  DIPPING RESERVOIR



INITIALIZATION DATA:

     NT=            1    NUMBER OF TIMES AT WHICH PRESSURE IS TC RE CALCULATED
     NW=            1    NUMBER OF WELLS TO BE CONSIDERED
     NRAD=          2    NUMBER CF POINTS AT WHICH PRESSURE IS TO BE CALCULATED


AQUIFER CHARACTERISTICS TO BE CONSIDERED:

     IVIS=          0    INJECTED FLUID TO HAVE VARIABLE VISCOSITY?  NO
     IMAGE=         0    AQUIFER CONFINED BY BOUNDARIES?  NO
     ILEAK=         0    VERTICAL AQUIFER LEAKAGE?  NO
     IDIP=          1    DIPPING BED? YES
     IPENT=         0    WELLS PARTIALLY PENETRATING BED?  NO
     IFRAC=         0    FRACTURE ANALYSIS?  NO
     IREF=          1    REFERENCF WELL FOR PRINTING


GENEFAL DATA CORRESPONDING TO OPTIONS SELECTED:

     CAPKT=       0.0    PERMEABILITY OF OVERLYING BED (MD)
     CAPHT=       0.0    THICKNESS OF OVERLYING BED (FT)
     CAPKB=       0.0    PERMEABILITY OF UNDERLYING BED (MD)
     CAPHB=       0.0    THICKNESS OF UNDERLYING BED (FT)
     ANGLE=       0.0    ANGLE OF BOUNDARY INTERSECTION (DEG)
     IB1=           0    BOUNDARY 1 SEALING OR LEAKING? SEAL
     IB2=           0    BOUNDARY 2 SEALING OR LEAKING? SEAL
     PI=          0.0    INTIAL RESERVOIR PRESSURE (PSI)
     DW=        65.50    DENSITY OF RESERVOIR FLUID (LB./CU. FT.)
```

```
                          RESERVOIR DESCRIPTIVE AND WELL COMPLETION
                                 INPUT DATA FOR WELL    1

TSTART=           0.0   TIME TO START OF FIRST RATE (DAYS)
PARTHK=           0.0   LENGTH OF WELL PENETRATION (FT)
PERMZ=            0.0   VERTICAL RESERVOIR PERMEABILITY (MD)
RADSKN=        100.00   RADIUS EFFECTED BY SKIN (FT)
PERM=           50.00   AREAL RESERVOIR PERMEABILITY (MD)
NRATE=              1   NUMBER OF RATES
VIS=            1.000   VISCOSITY OF RESERVOIR FLUID (CP)
SKIN=           0.0     SKIN FACTOR AT WELLBORE
POR=            0.150   RESERVOIR POROSITY (FRACTION)
TINS=           0.0     TIME TO START OF NEW FLUID INJECTION (DAYS)
THK=           45.00    RESERVOIR THICKNESS (FT)
VISN=           0.0     NEW FLUID VISCOSITY (CP)
BW=             1.00    FORMATION VOLUME FACTOR (RB/STB)
COMP=      0.00000750   SYSTEM COMPRESSIBILITY (1/PSI)
RW=             0.583   WELLBORE RADIUS (FT)
X=              0.0     REAL WELL X-LOCATION (FT)
XF=             0.0     FRACTURE LENGTH (FT)
Y=              0.0     REAL WELL Y-LOCATION (FT)
ZF=             0.0     DISTANCE FROM HORIZONTAL FRACTURE
DPENT=          0.0     DISTANCE FROM TOP OF ZONE TO TOP OF
                        PENETRATION (FT) (FT)


                                                    CUMULATIVE TIME
                         RATE        WELL RATE      TO END OF RATE
                        NUMBER      (STB/DAY)           DAYS

                         1           1714.00             0.0


                           DISTANCE TO POINT X FOR WELL    1
                                     CHANGE IN
                          POINT      ELEVATION            RADIUS
                          NUMBER       (FT)                (FT)

                            1            0.05                0.29
                            2          176.33             1000.00
```

```
 PRESSURE AT TIME   3650.000 (DAYS)

  POINT         RADIUS FROM        PRESSURE
 NUMBER       REFERENCE WELL        (PSIA)

    1                  0.292      1291.880
    2               1000.000       496.647
```

CHAPTER 6

SELECTED EXAMPLES OF FLUID INJECTION AND PRESSURE BUILDUP

It is of practical interest to examine a few selected examples of injection and pressure response and to compare such histories with the theoretical response that would be predicted on the basis of the equations presented earlier. Although injection through wells is widely practiced, probably the most closely monitored systems have been for industrial wastewater injection and the examples are based on such cases. The examples have been selected because they represent particularly significant regional disposal reservoirs and because sufficient data were available to allow the calculations and a comparison with actual performance.

TEXAS GULF COAST

Celanese Corporation, Harris County, Texas

As an example of the performance of injection wells in the Texas Gulf Coast area, the pressure buildup resulting from injection into two wells located in the Bayport Industrial Development, near Clear Lake City, Texas, will be studied (Figure 10). The wells began operation in 1967 and 1969, respectively, and their injection history through 1974 will be analyzed. The two wells were constructed for injection into a basal Miocene sand unit with an average thickness of 220 feet. The injection unit occurs at a depth of about 5300 feet. An observation well was installed to monitor the pressure buildup in the injection reservoir, as shown in Figure 10. The data used for the calculations are given below. The data were obtained from information in the files of the Texas Department of Water Resources, except for the reservoir compressibility, which is an assumed average value.

Parameter	Well TX-33	Well TX-45
P_i =	2394 psi	2394 psi
q =	7096 STB/D	4430 STB/D
β =	1	1
c =	7.5×10^{-6}psi^{-1}	7.5×10^{-6}psi^{-1}
k =	389 md	389 md

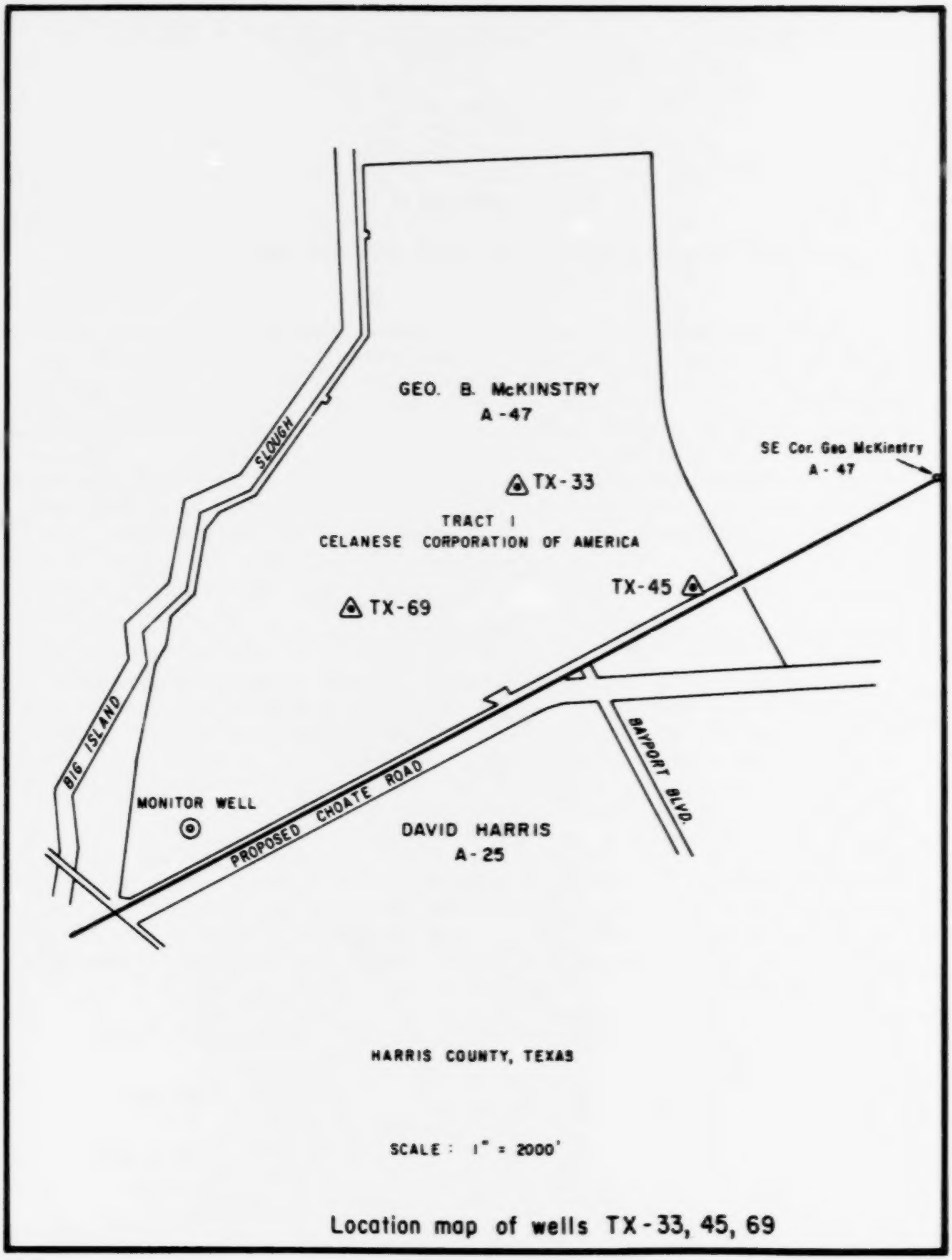

GEO. B. McKINSTRY
A -47
SE Cor. Geo McKinstry
A - 47
TX-33
TRACT I
CELANESE CORPORATION OF AMERICA
TX-45
TX-69
SLOUGH
BIG ISLAND
BAYPORT BLVD.
MONITOR WELL
PROPOSED CHOATE ROAD
DAVID HARRIS
A-25
HARRIS COUNTY, TEXAS
SCALE : 1" = 2000'
Location map of wells TX-33, 45, 69

Figure 10 Location map for Celanese Corporation wastewater injection and monitor wells, Harris County, Texas.

h =	220 ft	220 ft
ϕ =	0.30	0.30
μ =	0.55 cp	9.55 cp
r =	6224 ft	7652 ft
t =	2618 D	2040 D
s =	0	0

Using the programmable desk calculator, the reservoir pressure at the observation well at the end of 1974 can be calculated to be 2423 psi, an increase of 29 psi over the original reservoir pressure of 2394 psi. The observed pressure was 2438 psi. This is considered an adequate comparison. One possible reason for the difference between the observed and predicted values is that the wells were actually operated in an erratic manner, with considerable variation in injection rates and with periods in which the wells were not operated at all. The actual operating schedule could be simulated by using the variable rate equations that are presented; however, it would be extremely time consuming in this case and not worthwhile in view of the quite reasonable result obtained by using the constant rate equation. The result of assuming a constant average rate is, in any such situation, to predict a lower than actual pressure buildup, as has occurred in this case.

E.I. DuPont, Victoria, Texas

As a second Texas Gulf Coast example, the multiple well system at the E.I. DuPont, Victoria, Texas, plant will be considered. Injection at that site began in 1953, with one well and was expanded to a system of eight injection wells and a monitor well by 1974 (Figure 11). The pressure buildup at the monitor well resulting from injection during the period 1953 through December 1973 will be calculated. The data for use in the calculation are:

Parameter	Well No. 1
P_i =	1750 psi
q =	3572 STB/D
β =	1
c =	7.5×10^{-6} psi^{-1}
k =	828 md
h =	600 ft

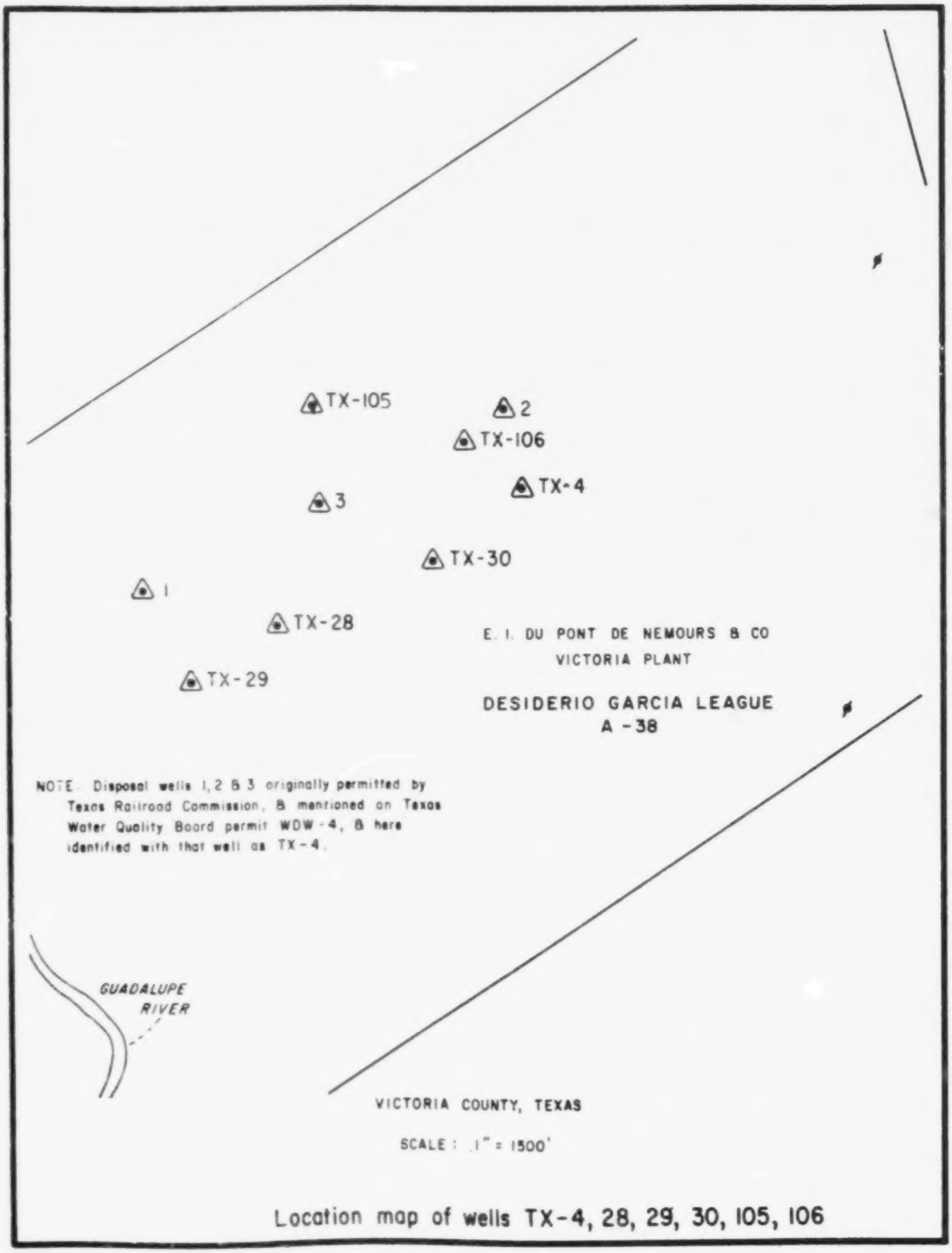

TX-105
2
TX-106
TX-4
3
TX-30
1
TX-28
TX-29
E. I. DU PONT DE NEMOURS & CO
VICTORIA PLANT
DESIDERIO GARCIA LEAGUE
A -38
NOTE: Disposal wells 1, 2 & 3 originally permitted by Texas Railroad Commission, & mentioned on Texas Water Quality Board permit WDW-4, & here identified with that well as TX-4.
GUADALUPE RIVER
VICTORIA COUNTY, TEXAS
SCALE: 1" = 1500'
Location map of wells TX-4, 28, 29, 30, 105, 106

Figure 11 Location map for E. I. DuPont Company injection and monitor wells, Victoria County, Texas.

ϕ = 0.31

μ = 0.75 cp

r = 2395 ft

t = 7665 days

s = 0

The data remain the same for the other seven injection wells, except for the injection rates, radii, and injection times, which are:

Parameter	Well No. 2	No. 3	TX-4	TX-28	TX-29	TX-105	TX-106
q(STB/D)	3733	3240	4812	8748	8594	2794	102
r(ft)	1650	1275	2025	1725	2700	1950	1275
t(D)	7300	5840	4015	2190	2190	730	365

Entering these data into the constant-rate, multiple-well desk calculator program, the reservoir pressure at the end of 1974 would be predicted to be 1782 psi. The observed pressure at the observation well ranged from about 1798 to 1814 psi during 1974, and was about 1813 psi at the end of the year. As in the previous example, the results are considered adequate in view of the simplified analysis used. In this case as in the previous one, injection rates were averaged to give a single constant rate. Data were obtained from files of the Texas Department of Water Resources, except for the reservoir compressibility, which is an assumed value. Distances from the injection wells to the observation well (TX-30) were measured from Figure 11.

FLORIDA

Wastewater injection is extensively practiced in Florida, where the injection reservoirs are carbonates of Tertiary age. One injection system that has been intensively monitored is that operated by the Monsanto Chemical Company near Pensacola, Florida. Two injection wells are used. The first began injection in 1964 and the second well was constructed in 1965. Both wells inject into the lower limestone of the Floridan aquifer, which occurs at a depth of about 1400 feet at the plant site. Although there are two injection wells, they can be treated as a single well when calculating pressure buildup at a location more than a few thousand feet away. The point to be considered is a monitor well located 10,000 feet north of the two injection wells. Other data needed for the calculation are given below. The data are from Goolsby (1972) and Faulkner and Pascale (1975). The pressure calculation is for late 1971, because Goolsby (1972) provides a cumulative injection volume for the two wells and the measured head at the monitor well for late 1971. Although injection rates varied between 1963 and 1971, an average rate is used.

P_i = 26 psi

q = 49,200 STB/D

β = 1

c = 1.32 x 10^{-5}

k = 878 md

h = 350 ft

ϕ = 0.10

μ = 1

r = 10,000 ft

t = 3000 D

s = 0

Entering these data into the single-well, constant-rate desk calculator program, the pressure buildup is calculated to be 64 psi and the total pressure 90 psi. For fresh water, this is a total head of 208 feet, which is approximately the head observed at the monitor well near the end of 1971, according to Goolsby (1972)

OHIO

An injection reservoir that is widely used in the north-central states, including Ohio, is the Mt. Simon Sandstone. The Mt. Simon is the basal sedimentary unit in that area, it is generally well separated from fresh-water-bearing aquifers, and it often has adequate reservoir properties for small to moderate amounts of injection. Data for an injection well in northern Ohio are:

P_i = 2750 psi

q = 2503 STB/D

β = 1

c = 7.5 x 10^{-6}

k = 6.3 md

$h = 255$ ft

$\phi = 0.08$

$\mu = 1.065$ cp

$r = 0.396$ ft (wellbore radius)

$t = 57$ D

$s = -2.8$

Entering these data into the single-well, constant-rate desk calculator program the total pressure at the end of 57 days is predicted to be 5172 psi and the predicted pressure buildup is, therefore, 1422 psi. The actual observed buildup was 1420 psi. Note that the skin factor in this case is -2.8, as a result of the well having been hydraulically fractured.

The data used in this example were derived from core analyses and well tests provided by the well operator. The accurate agreement between the predicted and observed results during the early phase of well operation indicate that considerable confidence could be placed in longer-term pressure buildup projections.

REFERENCES

Amyx, J. W., D. M. Bass, and R. L. Whiting. 1960. Petroleum Reservoir Engineering. McGraw-Hill Book Co. New York, N.Y. 610 pp.

Davis, S. N. and R. J. M. DeWiest. 1966. Hydrogeology. John Wiley and Sons, Inc. New York, N.Y. 463 pp.

Earlougher, R. C., Jr. 1977. Advances in Well Test Analysis. Soc. Petroleum Engineers. Monograph Volume 5. 264 pp.

Faulkner, G. L., and C. A. Pascale. 1975. Monitoring Regional Effects of High Pressure Injection of Industrial Waste in a Limestone Aquifer. Ground Water. Vol. 13. No. 2, pp. 197-208.

Goolsby, D. A. 1972. Geochemical Effects and Movement of Injected Industrial Waste in a Limestone Aquifer. in Underground Waste Management and Environmental Implications. T. D. Cook, ed. Am. Assoc. Petroleum Geologists Memoir 18, pp. 355-368.

Gringarten, A. C. and H. J. Ramey. 1974. Unsteady-State Pressure Distributions Created by a Well With a Single Horizontal Fracture, Partial Penetration, or Restricted Entry. Jour. Soc. Petroleum Engrs. August. pp. 413-426.

Gringarten, A. C., H. J. Ramey, and R. Raghaven. 1974. Unsteady-State Pressure Distributions Created by a Well With a Single Infinite-Conductivity Vertical Fracture. Jour. Soc. Petroleum Engrs. August. pp. 347-360.

Hantush, M. S., and C. E. Jacob. 1955. Nonsteady Radial Flow in an Infinite Leaky Aquifer. Trans. Am. Geophysical Union, V. 36, p. 95.

Hawkins, M. F., Jr. 1956. A Note on the Skin Effect. Trans. Am. Inst. Mining and Metallurgical Engrs. pp. 356-357.

Hubbert, M. K. and D. G. Willis. 1957. Mechanics of Hydraulic Fracturing. Trans. Am. Inst. Mining and Metallurgical Engrs. pp. 153-166.

Hurst, William. 1953. Establishment of the Skin Effect and Its Impediment to Fluid Flow Into a Well Bore. Petroleum Engineering. October. pp. B6-B16.

Matthews, C. S. and D. G. Russell. 1967. Pressure Buildup and Flow Tests in Wells. Soc. Petroleum Engineers Monograph Vol. 1. 178 pp.

National Bureau of Standards, 1964, Handbook of Mathematical Functions With Formulas, Graphs, and Mathematical Tables. Nat. Bureau of Stds. Applied Mathematics Series 55. U.S. Govt. Printing Office, Washington, D.C. 1046 pp.

Russell, D. G., and Prats, M. 1962. The Practical Aspects of Interlayer Cross-flow. Jour. Petroleum Technology. June. pp. 589-594.

Todd, D. K. 1959. Ground Water Hydrology. John Wiley and Sons, Inc. New York, N.Y. 335 pp.

Van Everdingen, A. F. 1953. The Skin Effect and Its Influence on the Productive Capacity of a Well. Trans. Am. Inst. Mining and Metallurgical Engrs. pp. 171-176.

Walton, W. C. 1970. Groundwater Resource Evaluation. McGraw-Hill Book Company, New York, N.Y. 664 pp.

Witherspoon, P.A., I. Javandel, S.P. Neuman, and R.A. Freeze. 1967. Interpretation of Aquifer Gas storage Conditions from Water Pumping Tests. American Gas Assoc. New York, N.Y. 273 pp.

APPENDIX A

TABLES FOR USE IN MANUAL PRESSURE BUILDUP CALCULATIONS

A-1 Values of the exponential integral - $E_1(x)$

A-2 Values of the error function - erf (x)

A-3 Values of the pseudo skin factor (σ) for the general vertical fracture case

A-4 Values of dimensionless pressure (P_{DL}) for semiconfined reservoirs

TABLE 1

VALUES OF E1(X)

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
				POWER OF 10 = -16						
1	36.2642	36.1688	36.0818	36.0018	35.9277	35.8587	35.7941	35.7335	35.6764	35.6223
2	35.5710	35.5222	35.4757	35.4312	35.3887	35.3479	35.3086	35.2709	35.2345	35.1994
3	35.1655	35.1328	35.1010	35.0702	35.0404	35.0114	34.9832	34.9558	34.9292	34.9032
4	34.8779	34.8532	34.8291	34.8055	34.7825	34.7601	34.7381	34.7166	34.6955	34.6749
5	34.6547	34.6349	34.6155	34.5965	34.5778	34.5594	34.5414	34.5237	34.5063	34.4892
6	34.4724	34.4559	34.4396	34.4236	34.4079	34.3923	34.3771	34.3620	34.3472	34.3326
7	34.3182	34.3041	34.2901	34.2763	34.2627	34.2493	34.2360	34.2229	34.2100	34.1973
8	34.1847	34.1723	34.1610	34.1479	34.1359	34.1241	34.1124	34.1008	34.0894	34.0781
9	34.0669	34.0559	34.0450	34.0341	34.0234	34.0129	34.0024	33.9920	33.9818	33.9716
				POWER OF 10 = -15						
1	33.9616	33.8663	33.7793	33.6992	33.6251	33.5561	33.4916	33.4309	33.3738	33.3197
2	33.2684	33.2196	33.1731	33.1287	33.0861	33.0453	33.0061	32.9683	32.9319	32.8969
3	32.8630	32.8302	32.7984	32.7676	32.7378	32.7088	32.6806	32.6532	32.6266	32.6006
4	32.5753	32.5506	32.5265	32.5030	32.4800	32.4575	32.4355	32.4140	32.3930	32.3723
5	32.3521	32.3323	32.3129	32.2939	32.2752	32.2568	32.2388	32.2211	32.2037	32.1866
6	32.1698	32.1533	32.1370	32.1210	32.1053	32.0898	32.0745	32.0595	32.0446	32.0300
7	32.0157	32.0015	31.9875	31.9737	31.9601	31.9467	31.9334	31.9203	31.9074	31.8947
8	31.8821	31.8697	31.8574	31.8453	31.8333	31.8215	31.8098	31.7982	31.7868	31.7755
9	31.7643	31.7533	31.7424	31.7316	31.7209	31.7103	31.6998	31.6894	31.6792	31.6690
				POWER OF 10 = -14						
1	31.6590	31.5637	31.4767	31.3966	31.3225	31.2535	31.1890	31.1284	31.0712	31.0171
2	30.9658	30.9171	30.8705	30.8261	30.7835	30.7427	30.7035	30.6657	30.6294	30.5943
3	30.5604	30.5276	30.4958	30.4651	30.4352	30.4062	30.3781	30.3506	30.3240	30.2980
4	30.2727	30.2480	30.2239	30.2004	30.1774	30.1549	30.1329	30.1114	30.0904	30.0697
5	30.0495	30.0297	30.0103	29.9913	29.9726	29.9542	29.9362	29.9185	29.9011	29.8840
6	29.8672	29.8507	29.8344	29.8184	29.8027	29.7872	29.7719	29.7569	29.7421	29.7275
7	29.7131	29.6989	29.6849	29.6711	29.6575	29.6441	29.6308	29.6178	29.6049	29.5921
8	29.5795	29.5671	29.5549	29.5427	29.5307	29.5189	29.5072	29.4957	29.4842	29.4729
9	29.4618	29.4507	29.4398	29.4290	29.4183	29.4077	29.3972	29.3869	29.3766	29.3665
				POWER OF 10 = -13						
1	29.3564	29.2611	29.1741	29.0940	29.0199	28.9509	28.8864	28.8258	28.7686	28.7145
2	28.6633	28.6145	28.5679	28.5235	28.4809	28.4401	28.4009	28.3631	28.3268	28.2917
3	28.2578	28.2250	28.1933	28.1625	28.1326	28.1036	28.0755	28.0481	28.0214	27.9954
4	27.9701	27.9454	27.9213	27.8978	27.8748	27.8523	27.8303	27.8088	27.7878	27.7672
5	27.7470	27.7272	27.7077	27.6887	27.6700	27.6517	27.6336	27.6159	27.5985	27.5815
6	27.5646	27.5481	27.5318	27.5159	27.5001	27.4846	27.4693	27.4543	27.4395	27.4249
7	27.4105	27.3963	27.3823	27.3685	27.3549	27.3415	27.3282	27.3152	27.3023	27.2895
8	27.2770	27.2645	27.2523	27.2401	27.2282	27.2163	27.2046	27.1931	27.1816	27.1703
9	27.1592	27.1481	27.1372	27.1264	27.1157	27.1051	27.0946	27.0843	27.0740	27.0639

TABLE 1
VALUES OF EI(X)

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
POWER OF 10 = -12										
1	27.0538	26.9585	26.8715	26.7915	26.7173	26.6483	26.5838	26.5232	26.4660	26.4120
2	26.3607	26.3119	26.2654	26.2209	26.1783	26.1375	26.0983	26.0606	26.0242	25.9891
3	25.9552	25.9224	25.8907	25.8599	25.8300	25.8011	25.7729	25.7455	25.7188	25.6928
4	25.6675	25.6428	25.6187	25.5952	25.5722	25.5497	25.5278	25.5063	25.4852	25.4646
5	25.4444	25.4246	25.4052	25.3861	25.3674	25.3491	25.3311	25.3134	25.2960	25.2789
6	25.2621	25.2455	25.2293	25.2133	25.1975	25.1820	25.1667	25.1517	25.1369	25.1223
7	25.1079	25.0937	25.0797	25.0659	25.0523	25.0389	25.0257	25.0126	24.9997	24.9870
8	24.9744	24.9619	24.9497	24.9376	24.9256	24.9137	24.9021	24.8905	24.8791	24.8678
9	24.8566	24.8455	24.8346	24.8238	24.8131	24.8025	24.7921	24.7817	24.7714	24.7613
POWER OF 10 = -11										
1	24.7512	24.6559	24.5689	24.4889	24.4147	24.3458	24.2812	24.2206	24.1634	24.1094
2	24.0581	24.0093	23.9628	23.9183	23.8758	23.8349	23.7957	23.7580	23.7216	23.6865
3	23.6526	23.6198	23.5881	23.5573	23.5275	23.4985	23.4703	23.4429	23.4162	23.3903
4	23.3649	23.3402	23.3161	23.2926	23.2696	23.2471	23.2252	23.2037	23.1826	23.1620
5	23.1418	23.1220	23.1026	23.0835	23.0648	23.0465	23.0285	23.0108	22.9934	22.9763
6	22.9595	22.9429	22.9267	22.9107	22.8949	22.8794	22.8642	22.8491	22.8343	22.8197
7	22.8053	22.7911	22.7771	22.7634	22.7497	22.7363	22.7231	22.7100	22.6971	22.6844
8	22.6718	22.6594	22.6471	22.6350	22.6230	22.6112	22.5995	22.5879	22.5765	22.5652
9	22.5540	22.5430	22.5320	22.5212	22.5105	22.4999	22.4895	22.4791	22.4688	22.4587
POWER OF 10 = -10										
1	22.4486	22.3533	22.2663	22.1863	22.1122	22.0432	21.9786	21.9180	21.8609	21.8068
2	21.7555	21.7067	21.6602	21.6157	21.5732	21.5323	21.4931	21.4554	21.4190	21.3839
3	21.3500	21.3172	21.2855	21.2547	21.2249	21.1959	21.1677	21.1403	21.1136	21.0877
4	21.0623	21.0377	21.0136	20.9900	20.9670	20.9446	20.9226	20.9011	20.8800	20.8594
5	20.8392	20.8194	20.8000	20.7809	20.7622	20.7439	20.7259	20.7082	20.6908	20.6737
6	20.6569	20.6404	20.6241	20.6081	20.5923	20.5768	20.5616	20.5465	20.5317	20.5171
7	20.5027	20.4886	20.4746	20.4608	20.4472	20.4337	20.4205	20.4074	20.3945	20.3818
8	20.3692	20.3568	20.3445	20.3324	20.3204	20.3086	20.2969	20.2853	20.2739	20.2626
9	20.2514	20.2404	20.2294	20.2186	20.2079	20.1974	20.1869	20.1765	20.1663	20.1561
POWER OF 10 = -9										
1	20.1461	20.0508	19.9637	19.8837	19.8096	19.7406	19.6761	19.6154	19.5583	19.5042
2	19.4529	19.4041	19.3576	19.3132	19.2706	19.2298	19.1906	19.1528	19.1164	19.0813
3	19.0474	19.0147	18.9829	18.9521	18.9223	18.8933	18.8651	18.8377	18.8111	18.7851
4	18.7598	18.7351	18.7110	18.6874	18.6645	18.6420	18.6200	18.5985	18.5774	18.5568
5	18.5366	18.5168	18.4974	18.4783	18.4597	18.4413	18.4233	18.4056	18.3882	18.3711
6	18.3543	18.3378	18.3215	18.3055	18.2898	18.2743	18.2590	18.2440	18.2291	18.2145
7	18.2001	18.1860	18.1720	18.1582	18.1446	18.1311	18.1179	18.1048	18.0919	18.0792
8	18.0666	18.0542	18.0419	18.0298	18.0178	18.0060	17.9943	17.9827	17.9713	17.9600
9	17.9488	17.9378	17.9268	17.9160	17.9053	17.8948	17.8843	17.8739	17.8637	17.8535

TABLE 1
VALUES OF E1(X)

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
POWER OF 10 = -8										
1	17.8435	17.7482	17.6611	17.5811	17.5070	17.4380	17.3735	17.3129	17.2557	17.2016
2	17.1503	17.1015	17.0550	17.0106	16.9680	16.9272	16.8880	16.8502	16.8139	16.7788
3	16.7449	16.7121	16.6803	16.6496	16.6197	16.5907	16.5625	16.5351	16.5085	16.4825
4	16.4572	16.4325	16.4084	16.3849	16.3619	16.3394	16.3174	16.2959	16.2749	16.2542
5	16.2340	16.2142	16.1948	16.1758	16.1571	16.1387	16.1207	16.1030	16.0856	16.0685
6	16.0517	16.0352	16.0189	16.0029	15.9872	15.9717	15.9564	15.9414	15.9266	15.9120
7	15.8976	15.8834	15.8694	15.8556	15.8420	15.8286	15.8153	15.8023	15.7894	15.7766
8	15.7640	15.7516	15.7393	15.7272	15.7152	15.7034	15.6917	15.6802	15.6687	15.6574
9	15.6463	15.6352	15.6243	15.6135	15.6028	15.5922	15.5817	15.5714	15.5611	15.5509
POWER OF 10 = -7										
1	15.5409	15.4456	15.3586	15.2785	15.2044	15.1354	15.0709	15.0103	14.9531	14.8990
2	14.8477	14.7990	14.7524	14.7080	14.6654	14.6246	14.5854	14.5476	14.5113	14.4762
3	14.4423	14.4095	14.3777	14.3470	14.3171	14.2881	14.2600	14.2326	14.2059	14.1799
4	14.1546	14.1299	14.1058	14.0823	14.0593	14.0368	14.0148	13.9933	13.9723	13.9517
5	13.9315	13.9117	13.8922	13.8732	13.8545	13.8361	13.8181	13.8004	13.7830	13.7659
6	13.7491	13.7326	13.7163	13.7003	13.6846	13.6691	13.6538	13.6388	13.6240	13.6094
7	13.5950	13.5808	13.5668	13.5530	13.5394	13.5260	13.5127	13.4997	13.4868	13.4740
8	13.4615	13.4490	13.4368	13.4246	13.4127	13.4008	13.3891	13.3776	13.3661	13.3548
9	13.3437	13.3326	13.3217	13.3109	13.3002	13.2896	13.2791	13.2688	13.2585	13.2484
POWER OF 10 = -6										
1	13.2383	13.1430	13.0560	12.9759	12.9018	12.8328	12.7683	12.7077	12.6505	12.5965
2	12.5452	12.4964	12.4499	12.4054	12.3628	12.3220	12.2828	12.2451	12.2087	12.1736
3	12.1397	12.1069	12.0752	12.0444	12.0145	11.9856	11.9574	11.9300	11.9033	11.8773
4	11.8520	11.8273	11.8032	11.7797	11.7567	11.7342	11.7123	11.6908	11.6697	11.6491
5	11.6289	11.6091	11.5897	11.5706	11.5519	11.5336	11.5155	11.4979	11.4805	11.4634
6	11.4466	11.4300	11.4138	11.3978	11.3820	11.3665	11.3512	11.3362	11.3214	11.3068
7	11.2924	11.2782	11.2642	11.2504	11.2368	11.2234	11.2102	11.1971	11.1842	11.1715
8	11.1589	11.1465	11.1342	11.1221	11.1101	11.0983	11.0866	11.0750	11.0636	11.0523
9	11.0411	11.0300	11.0191	11.0083	10.9976	10.9870	10.9766	10.9662	10.9559	10.9458
POWER OF 10 = -5										
1	10.9357	10.8404	10.7534	10.6734	10.5993	10.5303	10.4657	10.4051	10.3480	10.2939
2	10.2426	10.1938	10.1473	10.1028	10.0603	10.0195	9.9802	9.9425	9.9061	9.8710
3	9.8371	9.8044	9.7726	9.7418	9.7120	9.6830	9.6548	9.6274	9.6008	9.5748
4	9.5495	9.5248	9.5007	9.4772	9.4542	9.4317	9.4097	9.3882	9.3672	9.3465
5	9.3263	9.3065	9.2871	9.2681	9.2494	9.2310	9.2130	9.1953	9.1779	9.1608
6	9.1440	9.1275	9.1112	9.0952	9.0795	9.0640	9.0487	9.0337	9.0189	9.0043
7	8.9899	8.9757	8.9617	8.9479	8.9343	8.9209	8.9077	8.8946	8.8817	8.8689
8	8.8564	8.8439	8.8317	8.8196	8.8076	8.7957	8.7840	8.7725	8.7611	8.7498
9	8.7386	8.7275	8.7166	8.7058	8.6951	8.6845	8.6741	8.6637	8.6534	8.6433

TABLE 1
VALUES OF E1(X)

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
				POWER OF 10 = -4						
1	8.6332	8.5379	8.4509	8.3709	8.2968	8.2278	8.1633	8.1027	8.0455	7.9915
2	7.9402	7.8914	7.8449	7.8005	7.7579	7.7171	7.6779	7.6402	7.6038	7.5687
3	7.5348	7.5020	7.4703	7.4395	7.4097	7.3807	7.3526	7.3252	7.2985	7.2726
4	7.2472	7.2226	7.1985	7.1750	7.1520	7.1295	7.1075	7.0860	7.0650	7.0444
5	7.0242	7.0044	6.9850	6.9660	6.9473	6.9289	6.9109	6.8932	6.8759	6.8588
6	6.8420	6.8255	6.8092	6.7932	6.7775	6.7620	6.7467	6.7317	6.7169	6.7023
7	6.6879	6.6738	6.6598	6.6460	6.6324	6.6190	6.6058	6.5927	6.5798	6.5671
8	6.5545	6.5421	6.5298	6.5177	6.5057	6.4939	6.4822	6.4707	6.4593	6.4480
9	6.4368	6.4258	6.4149	6.4041	6.3934	6.3828	6.3723	6.3620	6.3517	6.3416
				POWER OF 10 = -3						
1	6.3316	6.2363	6.1494	6.0695	5.9955	5.9266	5.8622	5.8016	5.7446	5.6906
2	5.6394	5.5907	5.5443	5.4999	5.4575	5.4168	5.3776	5.3400	5.3037	5.2687
3	5.2349	5.2023	5.1706	5.1399	5.1102	5.0813	5.0532	5.0259	4.9994	4.9735
4	4.9483	4.9237	4.8997	4.8762	4.8533	4.8310	4.8091	4.7877	4.7667	4.7462
5	4.7261	4.7064	4.6871	4.6681	4.6495	4.6313	4.6134	4.5958	4.5785	4.5615
6	4.5448	4.5284	4.5122	4.4963	4.4806	4.4652	4.4501	4.4351	4.4204	4.4059
7	4.3916	4.3775	4.3637	4.3500	4.3365	4.3231	4.3100	4.2970	4.2842	4.2716
8	4.2591	4.2468	4.2346	4.2226	4.2107	4.1990	4.1874	4.1759	4.1646	4.1534
9	4.1423	4.1314	4.1205	4.1098	4.0992	4.0887	4.0784	4.0681	4.0579	4.0479
				POWER OF 10 = -2						
1	4.0379	3.9436	3.8576	3.7786	3.7054	3.6374	3.5739	3.5143	3.4581	3.4050
2	3.3547	3.3069	3.2614	3.2179	3.1764	3.1365	3.0983	3.0615	3.0262	2.9921
3	2.9591	2.9273	2.8966	2.8668	2.8379	2.8099	2.7827	2.7563	2.7306	2.7056
4	2.6813	2.6576	2.6344	2.6119	2.5899	2.5684	2.5474	2.5269	2.5068	2.4871
5	2.4679	2.4491	2.4306	2.4126	2.3949	2.3775	2.3604	2.3437	2.3273	2.3112
6	2.2953	2.2798	2.2645	2.2494	2.2347	2.2201	2.2058	2.1918	2.1779	2.1643
7	2.1509	2.1376	2.1246	2.1118	2.0991	2.0867	2.0744	2.0623	2.0504	2.0386
8	2.0270	2.0155	2.0042	1.9930	1.9820	1.9711	1.9604	1.9498	1.9393	1.9290
9	1.9188	1.9087	1.8987	1.8888	1.8791	1.8695	1.8600	1.8505	1.8412	1.8320
				POWER OF 10 = -1						
1	1.8229	1.7371	1.6596	1.5889	1.5242	1.4645	1.4092	1.3578	1.3098	1.2649
2	1.2227	1.1829	1.1454	1.1099	1.0763	1.0443	1.0139	0.9849	0.9573	0.9309
3	0.9057	0.8815	0.8584	0.8361	0.8148	0.7942	0.7745	0.7555	0.7371	0.7195
4	0.7024	0.6859	0.6700	0.6546	0.6397	0.6253	0.6114	0.5979	0.5848	0.5721
5	0.5598	0.5478	0.5362	0.5250	0.5140	0.5034	0.4930	0.4830	0.4732	0.4637
6	0.4544	0.4454	0.4366	0.4280	0.4197	0.4115	0.4036	0.3959	0.3883	0.3810
7	0.3738	0.3668	0.3599	0.3533	0.3467	0.3404	0.3341	0.3280	0.3221	0.3163
8	0.3106	0.3051	0.2996	0.2943	0.2891	0.2840	0.2791	0.2742	0.2694	0.2648
9	0.2602	0.2557	0.2513	0.2470	0.2428	0.2387	0.2347	0.2308	0.2269	0.2231

TABLE 1
VALUES OF E1(X)

POWER OF 10 = 0

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
1	0.2194	0.1860	0.1584	0.1355	0.1162	0.1000	0.0863	0.0746	0.0647	0.0561
2	0.0489	0.0426	0.0372	0.0325	0.0284	0.0249	0.0218	0.0191	0.0167	0.0146
3	0.0131	0.0115	0.0101	0.0090	0.0079	0.0070	0.0062	0.0055	0.0048	0.0043
4	0.0038	0.0034	0.0030	0.0026	0.0024	0.0021	0.0019	0.0016	0.0015	0.0013
5	0.0012	0.0010	0.0009	0.0008	0.0007	0.0007	0.0006	0.0005	0.0005	0.0004
6	0.0004	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001
7	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
8	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
9	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

TABLE 2
VALUES OF ERF(X)

```
           0.0     0.1000  0.2000  0.3000  0.4000  0.5000  0.6000  0.7000  0.8000  0.9000

           POWER OF 10 =   -1              (MULTIPLY TABULAR VALUES BY 1.0000)
   1       0.1125  0.1236  0.1348  0.1459  0.1569  0.1680  0.1790  0.1900  0.2009  0.2118
   2       0.2227  0.2335  0.2443  0.2550  0.2657  0.2763  0.2869  0.2974  0.3079  0.3183
   3       0.3286  0.3389  0.3491  0.3593  0.3694  0.3794  0.3893  0.3992  0.4090  0.4187
   4       0.4284  0.4380  0.4475  0.4569  0.4662  0.4755  0.4847  0.4937  0.5027  0.5117
   5       0.5205  0.5292  0.5379  0.5465  0.5549  0.5633  0.5716  0.5798  0.5879  0.5959
   6       0.6039  0.6117  0.6194  0.6270  0.6346  0.6420  0.6494  0.6566  0.6638  0.6708
   7       0.6778  0.6847  0.6914  0.6981  0.7047  0.7112  0.7175  0.7238  0.7300  0.7361
   8       0.7421  0.7480  0.7538  0.7595  0.7651  0.7707  0.7761  0.7814  0.7867  0.7918
   9       0.7969  0.8019  0.8068  0.8116  0.8163  0.8209  0.8254  0.8299  0.8342  0.8385

           0.0     0.0100  0.0200  0.0300  0.0400  0.0500  0.0600  0.0700  0.0800  0.0900

           POWER OF 10 =   0               (MULTIPLY TABULAR VALUES BY 1.0000)
 1.0       0.8427  0.8468  0.8508  0.8548  0.8586  0.8624  0.8661  0.8698  0.8733  0.8768
 1.1       0.8802  0.8835  0.8868  0.8900  0.8931  0.8961  0.8991  0.9020  0.9048  0.9076
 1.2       0.9103  0.9130  0.9155  0.9181  0.9205  0.9229  0.9252  0.9275  0.9297  0.9319
 1.3       0.9340  0.9361  0.9381  0.9400  0.9419  0.9438  0.9456  0.9473  0.9490  0.9507
 1.4       0.9523  0.9539  0.9554  0.9569  0.9583  0.9597  0.9611  0.9624  0.9637  0.9649
 1.5       0.9661  0.9673  0.9684  0.9695  0.9706  0.9716  0.9726  0.9736  0.9745  0.9755
 1.6       0.9763  0.9772  0.9780  0.9788  0.9796  0.9804  0.9811  0.9818  0.9825  0.9832
 1.7       0.9838  0.9844  0.9850  0.9856  0.9861  0.9867  0.9872  0.9877  0.9882  0.9886
 1.8       0.9891  0.9895  0.9899  0.9903  0.9907  0.9911  0.9915  0.9918  0.9922  0.9925
 1.9       0.9928  0.9931  0.9934  0.9937  0.9939  0.9942  0.9944  0.9947  0.9949  0.9951

           POWER OF 10 =   0               (MULTIPLY TABULAR VALUES BY 1.0000)
 2.0       0.9953  0.9955  0.9957  0.9959  0.9961  0.9963  0.9964  0.9966  0.9967  0.9969
 2.1       0.9970  0.9972  0.9973  0.9974  0.9975  0.9976  0.9977  0.9979  0.9980  0.9980
 2.2       0.9981  0.9982  0.9983  0.9984  0.9985  0.9985  0.9986  0.9987  0.9987  0.9988
 2.3       0.9989  0.9989  0.9990  0.9990  0.9991  0.9991  0.9992  0.9992  0.9992  0.9993
 2.4       0.9993  0.9993  0.9994  0.9994  0.9994  0.9995  0.9995  0.9995  0.9995  0.9996
 2.5       0.9996  0.9996  0.9996  0.9997  0.9997  0.9997  0.9997  0.9997  0.9997  0.9998
 2.6       0.9998  0.9998  0.9998  0.9998  0.9998  0.9998  0.9998  0.9998  0.9998  0.9999
 2.7       0.9999  0.9999  0.9999  0.9999  0.9999  0.9999  0.9999  0.9999  0.9999  0.9999
 2.8       0.9999  0.9999  0.9999  0.9999  0.9999  0.9999  0.9999  1.0000  1.0000  1.0000
 2.9       1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000  1.0000
```

TABLE 2
VALUES OF ERF(X)

	0.0	0.1000	0.2000	0.3000	0.4000	0.5000	0.6000	0.7000	0.8000	0.9000
	POWER OF 10 = -5				(MULTIPLY TABULAR VALUES BY 0.0010)					
1	0.0113	0.0124	0.0135	0.0147	0.0158	0.0169	0.0181	0.0192	0.0203	0.0214
2	0.0226	0.0237	0.0248	0.0260	0.0271	0.0282	0.0293	0.0305	0.0316	0.0327
3	0.0339	0.0350	0.0361	0.0372	0.0384	0.0395	0.0406	0.0418	0.0429	0.0440
4	0.0451	0.0463	0.0474	0.0485	0.0496	0.0508	0.0519	0.0530	0.0542	0.0553
5	0.0564	0.0575	0.0587	0.0598	0.0609	0.0621	0.0632	0.0643	0.0654	0.0666
6	0.0677	0.0688	0.0700	0.0711	0.0722	0.0733	0.0745	0.0756	0.0767	0.0779
7	0.0790	0.0801	0.0812	0.0824	0.0835	0.0846	0.0858	0.0869	0.0880	0.0891
8	0.0903	0.0914	0.0925	0.0937	0.0948	0.0959	0.0970	0.0982	0.0993	0.1004
9	0.1016	0.1027	0.1038	0.1049	0.1061	0.1072	0.1083	0.1095	0.1106	0.1117
	POWER OF 10 = -4				(MULTIPLY TABULAR VALUES BY 0.0100)					
1	0.0113	0.0124	0.0135	0.0147	0.0158	0.0169	0.0181	0.0192	0.0203	0.0214
2	0.0226	0.0237	0.0248	0.0260	0.0271	0.0282	0.0293	0.0305	0.0316	0.0327
3	0.0339	0.0350	0.0361	0.0372	0.0384	0.0395	0.0406	0.0418	0.0429	0.0440
4	0.0451	0.0463	0.0474	0.0485	0.0496	0.0508	0.0519	0.0530	0.0542	0.0553
5	0.0564	0.0575	0.0587	0.0598	0.0609	0.0621	0.0632	0.0643	0.0654	0.0666
6	0.0677	0.0688	0.0700	0.0711	0.0722	0.0733	0.0745	0.0756	0.0767	0.0779
7	0.0790	0.0801	0.0812	0.0824	0.0835	0.0846	0.0858	0.0869	0.0880	0.0891
8	0.0903	0.0914	0.0925	0.0937	0.0948	0.0959	0.0970	0.0982	0.0993	0.1004
9	0.1016	0.1027	0.1038	0.1049	0.1061	0.1072	0.1083	0.1095	0.1106	0.1117
	POWER OF 10 = -3				(MULTIPLY TABULAR VALUES BY 0.1000)					
1	0.0113	0.0124	0.0135	0.0147	0.0158	0.0169	0.0181	0.0192	0.0203	0.0214
2	0.0226	0.0237	0.0248	0.0260	0.0271	0.0282	0.0293	0.0305	0.0316	0.0327
3	0.0339	0.0350	0.0361	0.0372	0.0384	0.0395	0.0406	0.0417	0.0429	0.0440
4	0.0451	0.0463	0.0474	0.0485	0.0496	0.0508	0.0519	0.0530	0.0542	0.0553
5	0.0564	0.0575	0.0587	0.0598	0.0609	0.0621	0.0632	0.0643	0.0654	0.0666
6	0.0677	0.0688	0.0700	0.0711	0.0722	0.0733	0.0745	0.0756	0.0767	0.0779
7	0.0790	0.0801	0.0812	0.0824	0.0835	0.0846	0.0858	0.0869	0.0880	0.0891
8	0.0903	0.0914	0.0925	0.0937	0.0948	0.0959	0.0970	0.0982	0.0993	0.1004
9	0.1016	0.1027	0.1038	0.1049	0.1061	0.1072	0.1083	0.1094	0.1106	0.1117
	POWER OF 10 = -2				(MULTIPLY TABULAR VALUES BY 1.0000)					
1	0.0113	0.0124	0.0135	0.0147	0.0158	0.0169	0.0181	0.0192	0.0203	0.0214
2	0.0226	0.0237	0.0248	0.0259	0.0271	0.0282	0.0293	0.0305	0.0316	0.0327
3	0.0338	0.0350	0.0361	0.0372	0.0384	0.0395	0.0406	0.0417	0.0429	0.0440
4	0.0451	0.0462	0.0474	0.0485	0.0496	0.0507	0.0519	0.0530	0.0541	0.0552
5	0.0564	0.0575	0.0586	0.0597	0.0609	0.0620	0.0631	0.0642	0.0654	0.0665
6	0.0676	0.0687	0.0699	0.0710	0.0721	0.0732	0.0744	0.0755	0.0766	0.0777
7	0.0789	0.0800	0.0811	0.0822	0.0833	0.0845	0.0856	0.0867	0.0878	0.0890
8	0.0901	0.0912	0.0923	0.0934	0.0946	0.0957	0.0968	0.0979	0.0990	0.1002
9	0.1013	0.1024	0.1035	0.1046	0.1058	0.1069	0.1080	0.1091	0.1102	0.1113

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                                     TABLE 3
                    VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)
                                    POWER OF 10 APPLICABLE TO YD=  -2
      YD=      0.0      1.000     2.000     3.000     4.000     5.000     6.000     7.000     8.000     9.000
                                    POWER OF 10 APPLICABLE TO XD=  -2
 XD=   0       0.0     -0.000    -0.000    -0.000    -0.001    -0.001    -0.002    -0.002    -0.003    -0.004
       1     -0.000    -0.000    -0.000    -0.000    -0.001    -0.001    -0.002    -0.002    -0.003    -0.004
       2     -0.000    -0.000    -0.000    -0.001    -0.001    -0.001    -0.002    -0.003    -0.003    -0.004
       3     -0.000    -0.001    -0.001    -0.001    -0.001    -0.002    -0.002    -0.003    -0.004    -0.004
       4     -0.001    -0.001    -0.001    -0.001    -0.002    -0.002    -0.003    -0.003    -0.004    -0.005
       5     -0.001    -0.001    -0.001    -0.002    -0.002    -0.003    -0.003    -0.004    -0.004    -0.005
       6     -0.002    -0.002    -0.002    -0.002    -0.003    -0.003    -0.004    -0.004    -0.005    -0.006
       7     -0.002    -0.003    -0.003    -0.003    -0.003    -0.004    -0.004    -0.005    -0.006    -0.007
       8     -0.003    -0.003    -0.003    -0.004    -0.004    -0.004    -0.005    -0.006    -0.006    -0.007
       9     -0.004    -0.004    -0.004    -0.005    -0.005    -0.005    -0.006    -0.007    -0.007    -0.008
                                    POWER OF 10 APPLICABLE TO XD=  -1
 XD=   0       0.0     -0.000    -0.000    -0.000    -0.001    -0.001    -0.002    -0.002    -0.003    -0.004
       1     -0.005    -0.005    -0.005    -0.005    -0.006    -0.006    -0.007    -0.007    -0.008    -0.009
       2     -0.020    -0.020    -0.020    -0.021    -0.021    -0.021    -0.022    -0.023    -0.023    -0.024
       3     -0.046    -0.046    -0.046    -0.046    -0.047    -0.047    -0.048    -0.048    -0.049    -0.050
       4     -0.082    -0.082    -0.083    -0.083    -0.083    -0.084    -0.084    -0.085    -0.086    -0.087
       5     -0.131    -0.131    -0.131    -0.131    -0.132    -0.132    -0.133    -0.134    -0.135    -0.136
       6     -0.193    -0.193    -0.193    -0.193    -0.194    -0.195    -0.196    -0.197    -0.198    -0.199
       7     -0.270    -0.271    -0.271    -0.271    -0.272    -0.273    -0.274    -0.275    -0.277    -0.278
       8     -0.368    -0.368    -0.369    -0.369    -0.370    -0.371    -0.373    -0.375    -0.376    -0.378
       9     -0.495    -0.495    -0.496    -0.497    -0.499    -0.501    -0.503    -0.505    -0.508    -0.511
                                    POWER OF 10 APPLICABLE TO XD=   0
 XD=   0       0.0     -0.000    -0.000    -0.000    -0.001    -0.001    -0.002    -0.002    -0.003    -0.004
       1     *******   -0.701    -0.709    -0.717    -0.724    -0.732    -0.740    -0.748    -0.755    -0.763
       2     -1.648    -1.648    -1.648    -1.648    -1.648    -1.648    -1.649    -1.649    -1.649    -1.649
       3     -2.079    -2.079    -2.079    -2.079    -2.080    -2.080    -2.080    -2.080    -2.080    -2.080
       4     -2.376    -2.376    -2.376    -2.376    -2.376    -2.376    -2.376    -2.376    -2.376    -2.376
       5     -2.603    -2.603    -2.603    -2.603    -2.603    -2.603    -2.603    -2.603    -2.603    -2.603
       6     -2.787    -2.787    -2.787    -2.787    -2.787    -2.787    -2.787    -2.787    -2.787    -2.787
       7     -2.942    -2.942    -2.942    -2.942    -2.943    -2.943    -2.943    -2.943    -2.943    -2.943
       8     -3.077    -3.077    -3.077    -3.077    -3.077    -3.077    -3.077    -3.077    -3.077    -3.077
       9     -3.195    -3.195    -3.195    -3.195    -3.195    -3.195    -3.195    -3.195    -3.195    -3.195
                                    POWER OF 10 APPLICABLE TO XD=   1
 XD=   0       0.0     -0.000    -0.000    -0.000    -0.001    -0.001    -0.002    -0.002    -0.003    -0.004
       1     -3.301    -3.301    -3.301    -3.301    -3.301    -3.301    -3.301    -3.301    -3.301    -3.301
       2     -3.995    -3.995    -3.995    -3.995    -3.995    -3.995    -3.995    -3.995    -3.995    -3.995
       3     -4.401    -4.401    -4.401    -4.401    -4.401    -4.401    -4.401    -4.401    -4.401    -4.401
       4     -4.689    -4.689    -4.689    -4.689    -4.689    -4.689    -4.689    -4.689    -4.689    -4.689
       5     -4.912    -4.912    -4.912    -4.912    -4.912    -4.912    -4.912    -4.912    -4.912    -4.912
       6     -5.094    -5.094    -5.094    -5.094    -5.094    -5.094    -5.094    -5.094    -5.094    -5.094
       7     -5.248    -5.248    -5.248    -5.248    -5.248    -5.248    -5.248    -5.248    -5.248    -5.248
       8     -5.382    -5.382    -5.382    -5.382    -5.382    -5.382    -5.382    -5.382    -5.382    -5.382
       9     -5.500    -5.500    -5.500    -5.500    -5.500    -5.500    -5.500    -5.500    -5.500    -5.500
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                                       TABLE 3
                       VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)

                                       POWER OF 10 APPLICABLE TO YD=  -2
       YD=      0.0     1.000    2.000    3.000    4.000    5.000    6.000    7.000    8.000    9.000

                                       POWER OF 10 APPLICABLE TO XD=   2
  XD=   0      0.0     -0.000   -0.000   -0.000   -0.001   -0.001   -0.002   -0.002   -0.003   -0.004
        1     -5.605   -5.605   -5.605   -5.605   -5.605   -5.605   -5.605   -5.605   -5.605   -5.605
        2     -6.298   -6.298   -6.298   -6.298   -6.298   -6.298   -6.298   -6.298   -6.298   -6.298
        3     -6.704   -6.704   -6.704   -6.704   -6.704   -6.704   -6.704   -6.704   -6.704   -6.704
        4     -6.991   -6.991   -6.991   -6.991   -6.991   -6.991   -6.991   -6.991   -6.991   -6.991
        5     -7.215   -7.215   -7.215   -7.215   -7.215   -7.215   -7.215   -7.215   -7.215   -7.215
        6     -7.397   -7.397   -7.397   -7.397   -7.397   -7.397   -7.397   -7.397   -7.397   -7.397
        7     -7.551   -7.551   -7.551   -7.551   -7.551   -7.551   -7.551   -7.551   -7.551   -7.551
        8     -7.685   -7.685   -7.685   -7.685   -7.685   -7.685   -7.685   -7.685   -7.685   -7.685
        9     -7.802   -7.802   -7.802   -7.802   -7.802   -7.802   -7.802   -7.802   -7.802   -7.802

                                       POWER OF 10 APPLICABLE TO XD=   3
  XD=   0      0.0     -0.000   -0.000   -0.000   -0.001   -0.001   -0.002   -0.002   -0.003   -0.004
        1     -7.908   -7.908   -7.908   -7.908   -7.908   -7.908   -7.908   -7.908   -7.908   -7.908
        2     -8.601   -8.601   -8.601   -8.601   -8.601   -8.601   -8.601   -8.601   -8.601   -8.601
        3     -9.006   -9.006   -9.006   -9.006   -9.006   -9.006   -9.006   -9.006   -9.006   -9.006
        4     -9.294   -9.294   -9.294   -9.294   -9.294   -9.294   -9.294   -9.294   -9.294   -9.294
        5     -9.517   -9.517   -9.517   -9.517   -9.517   -9.517   -9.517   -9.517   -9.517   -9.517
        6     -9.700   -9.700   -9.700   -9.700   -9.700   -9.700   -9.700   -9.700   -9.700   -9.700
        7     -9.854   -9.854   -9.854   -9.854   -9.854   -9.854   -9.854   -9.854   -9.854   -9.854
        8     -9.987   -9.987   -9.987   -9.987   -9.987   -9.987   -9.987   -9.987   -9.987   -9.987
        9    -10.105  -10.105  -10.105  -10.105  -10.105  -10.105  -10.105  -10.105  -10.105  -10.105

                                       POWER OF 10 APPLICABLE TO XD=   4
  XD=   0      0.0     -0.000   -0.000   -0.000   -0.001   -0.001   -0.002   -0.002   -0.003   -0.004
        1    -10.210  -10.210  -10.210  -10.210  -10.210  -10.210  -10.210  -10.210  -10.210  -10.210
        2    -10.903  -10.903  -10.903  -10.903  -10.903  -10.903  -10.903  -10.903  -10.903  -10.903
        3    -11.309  -11.309  -11.309  -11.309  -11.309  -11.309  -11.309  -11.309  -11.309  -11.309
        4    -11.597  -11.597  -11.597  -11.597  -11.597  -11.597  -11.597  -11.597  -11.597  -11.597
        5    -11.820  -11.820  -11.820  -11.820  -11.820  -11.820  -11.820  -11.820  -11.820  -11.820
        6    -12.002  -12.002  -12.002  -12.002  -12.002  -12.002  -12.002  -12.002  -12.002  -12.002
        7    -12.156  -12.156  -12.156  -12.156  -12.156  -12.156  -12.156  -12.156  -12.156  -12.156
        8    -12.290  -12.290  -12.290  -12.290  -12.290  -12.290  -12.290  -12.290  -12.290  -12.290
        9    -12.408  -12.408  -12.408  -12.408  -12.408  -12.408  -12.408  -12.408  -12.408  -12.408
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                                           TABLE 3
                         VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)

                                          POWER OF 10 APPLICABLE TO YD=   -1
          YD=        0.0       1.000     2.000     3.000     4.000     5.000     6.000     7.000     8.000     9.000

                                          POWER OF 10 APPLICABLE TO XD=   -2
   XD=     0         0.0      -0.005    -0.020    -0.043    -0.074    -0.112    -0.154    -0.199    -0.247    -0.297
           1        -0.000    -0.005    -0.020    -0.043    -0.074    -0.112    -0.154    -0.199    -0.247    -0.297
           2        -0.000    -0.005    -0.020    -0.043    -0.074    -0.112    -0.154    -0.200    -0.248    -0.297
           3        -0.000    -0.005    -0.020    -0.044    -0.075    -0.112    -0.154    -0.200    -0.248    -0.297
           4        -0.001    -0.006    -0.020    -0.044    -0.075    -0.112    -0.155    -0.200    -0.248    -0.298
           5        -0.001    -0.006    -0.021    -0.044    -0.076    -0.113    -0.155    -0.201    -0.249    -0.298
           6        -0.002    -0.007    -0.021    -0.045    -0.076    -0.114    -0.156    -0.201    -0.249    -0.299
           7        -0.002    -0.007    -0.022    -0.046    -0.077    -0.114    -0.156    -0.202    -0.250    -0.299
           8        -0.003    -0.008    -0.023    -0.047    -0.078    -0.115    -0.157    -0.203    -0.251    -0.300
           9        -0.004    -0.009    -0.024    -0.047    -0.079    -0.116    -0.158    -0.204    -0.252    -0.301

                                          POWER OF 10 APPLICABLE TO XD=   -1
   XD=     0         0.0      -0.005    -0.020    -0.043    -0.074    -0.112    -0.154    -0.199    -0.247    -0.297
           1        -0.005    -0.010    -0.025    -0.048    -0.080    -0.117    -0.159    -0.205    -0.253    -0.302
           2        -0.020    -0.025    -0.040    -0.065    -0.096    -0.134    -0.176    -0.222    -0.269    -0.318
           3        -0.046    -0.051    -0.067    -0.092    -0.125    -0.163    -0.205    -0.250    -0.296    -0.344
           4        -0.082    -0.088    -0.105    -0.131    -0.165    -0.203    -0.245    -0.289    -0.334    -0.380
           5        -0.131    -0.137    -0.156    -0.184    -0.218    -0.257    -0.298    -0.340    -0.383    -1.119
           6        -0.193    -0.200    -0.221    -0.251    -0.286    -0.324    -0.363    -0.403    -0.443    -1.147
           7        -0.270    -0.280    -0.304    -0.335    -0.370    -0.405    -0.441    -0.477    -1.108    -1.181
           8        -0.368    -0.381    -0.408    -0.439    -0.470    -0.501    -0.531    -1.078    -1.150    -1.218
           9        -0.495    -0.513    -0.540    -0.564    -0.586    -0.986    -1.059    -1.129    -1.195    -1.259

                                          POWER OF 10 APPLICABLE TO XD=    0
   XD=     0         0.0      -0.005    -0.020    -0.043    -0.074    -0.112    -0.154    -0.199    -0.247    -0.297
           1       *******    -0.770    -0.845    -0.918    -0.987    -1.055    -1.120    -1.183    -1.243    -1.302
           2        -1.648    -1.650    -1.655    -1.663    -1.674    -1.687    -1.703    -1.722    -1.741    -1.763
           3        -2.079    -2.080    -2.082    -2.085    -2.089    -2.095    -2.101    -2.109    -2.118    -2.127
           4        -2.376    -2.376    -2.377    -2.379    -2.381    -2.384    -2.388    -2.392    -2.397    -2.402
           5        -2.603    -2.603    -2.604    -2.605    -2.606    -2.608    -2.610    -2.613    -2.616    -2.619
           6        -2.787    -2.787    -2.788    -2.788    -2.789    -2.791    -2.792    -2.794    -2.796    -2.799
           7        -2.942    -2.943    -2.943    -2.943    -2.944    -2.945    -2.946    -2.948    -2.949    -2.951
           8        -3.077    -3.077    -3.077    -3.078    -3.078    -3.079    -3.080    -3.081    -3.082    -3.083
           9        -3.195    -3.195    -3.195    -3.196    -3.196    -3.197    -3.197    -3.198    -3.199    -3.200

                                          POWER OF 10 APPLICABLE TO XD=    1
   XD=     0         0.0      -0.005    -0.020    -0.043    -0.074    -0.112    -0.154    -0.199    -0.247    -0.297
           1        -3.301    -3.301    -3.301    -3.301    -3.302    -3.302    -3.303    -3.303    -3.304    -3.305
           2        -3.995    -3.995    -3.995    -3.995    -3.996    -3.996    -3.996    -3.996    -3.996    -3.996
           3        -4.401    -4.401    -4.401    -4.401    -4.401    -4.401    -4.401    -4.401    -4.401    -4.401
           4        -4.689    -4.689    -4.689    -4.689    -4.689    -4.689    -4.689    -4.689    -4.689    -4.689
           5        -4.912    -4.912    -4.912    -4.912    -4.912    -4.912    -4.912    -4.912    -4.912    -4.912
           6        -5.094    -5.094    -5.094    -5.094    -5.094    -5.094    -5.094    -5.094    -5.094    -5.094
           7        -5.248    -5.248    -5.248    -5.248    -5.248    -5.248    -5.248    -5.249    -5.249    -5.249
           8        -5.382    -5.382    -5.382    -5.382    -5.382    -5.382    -5.382    -5.382    -5.382    -5.382
           9        -5.500    -5.500    -5.500    -5.500    -5.500    -5.500    -5.500    -5.500    -5.500    -5.500
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                                        TABLE 3
                    VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)

                                  POWER OF 10 APPLICABLE TO YD=  -1
        YD=      0.0     1.000     2.000     3.000     4.000     5.000     6.000     7.000     8.000     9.000

                                  POWER OF 10 APPLICABLE TO XD=   2
 XD=     0       0.0    -0.005    -0.020    -0.043    -0.074    -0.112    -0.154    -0.199    -0.247    -0.297
         1    -5.605    -5.605    -5.605    -5.605    -5.605    -5.605    -5.605    -5.605    -5.605    -5.605
         2    -6.298    -6.298    -6.298    -6.298    -6.298    -6.298    -6.298    -6.298    -6.298    -6.298
         3    -6.704    -6.704    -6.704    -6.704    -6.704    -6.704    -6.704    -6.704    -6.704    -6.704
         4    -6.991    -6.991    -6.991    -6.991    -6.991    -6.991    -6.991    -6.991    -6.991    -6.991
         5    -7.215    -7.215    -7.215    -7.215    -7.215    -7.215    -7.215    -7.215    -7.215    -7.215
         6    -7.397    -7.397    -7.397    -7.397    -7.397    -7.397    -7.397    -7.397    -7.397    -7.397
         7    -7.551    -7.551    -7.551    -7.551    -7.551    -7.551    -7.551    -7.551    -7.551    -7.551
         8    -7.685    -7.685    -7.685    -7.685    -7.685    -7.685    -7.685    -7.685    -7.685    -7.685
         9    -7.802    -7.802    -7.802    -7.802    -7.802    -7.802    -7.802    -7.802    -7.802    -7.802

                                  POWER OF 10 APPLICABLE TO XD=   3
 XD=     0       0.0    -0.005    -0.020    -0.043    -0.074    -0.112    -0.154    -0.199    -0.247    -0.297
         1    -7.908    -7.908    -7.908    -7.908    -7.908    -7.908    -7.908    -7.908    -7.908    -7.908
         2    -8.601    -8.601    -8.601    -8.601    -8.601    -8.601    -8.601    -8.601    -8.601    -8.601
         3    -9.006    -9.006    -9.006    -9.006    -9.006    -9.006    -9.006    -9.006    -9.006    -9.006
         4    -9.294    -9.294    -9.294    -9.294    -9.294    -9.294    -9.294    -9.294    -9.294    -9.294
         5    -9.517    -9.517    -9.517    -9.517    -9.517    -9.517    -9.517    -9.517    -9.517    -9.517
         6    -9.700    -9.700    -9.700    -9.700    -9.700    -9.700    -9.700    -9.700    -9.700    -9.700
         7    -9.854    -9.854    -9.854    -9.854    -9.854    -9.854    -9.854    -9.854    -9.854    -9.854
         8    -9.987    -9.987    -9.987    -9.987    -9.987    -9.987    -9.987    -9.987    -9.987    -9.987
         9   -10.105   -10.105   -10.105   -10.105   -10.105   -10.105   -10.105   -10.105   -10.105   -10.105

                                  POWER OF 10 APPLICABLE TO XD=   4
 XD=     0       0.0    -0.005    -0.020    -0.043    -0.074    -0.112    -0.154    -0.199    -0.247    -0.297
         1   -10.210   -10.210   -10.210   -10.210   -10.210   -10.210   -10.210   -10.210   -10.210   -10.210
         2   -10.903   -10.903   -10.903   -10.903   -10.903   -10.903   -10.903   -10.903   -10.903   -10.903
         3   -11.309   -11.309   -11.309   -11.309   -11.309   -11.309   -11.309   -11.309   -11.309   -11.309
         4   -11.597   -11.597   -11.597   -11.597   -11.597   -11.597   -11.597   -11.597   -11.597   -11.597
         5   -11.820   -11.820   -11.820   -11.820   -11.820   -11.820   -11.820   -11.820   -11.820   -11.820
         6   -12.002   -12.002   -12.002   -12.002   -12.002   -12.002   -12.002   -12.002   -12.002   -12.002
         7   -12.156   -12.156   -12.156   -12.156   -12.156   -12.156   -12.156   -12.156   -12.156   -12.156
         8   -12.290   -12.290   -12.290   -12.290   -12.290   -12.290   -12.290   -12.290   -12.290   -12.290
         9   -12.408   -12.408   -12.408   -12.408   -12.408   -12.408   -12.408   -12.408   -12.408   -12.408
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                                        TABLE 3
                       VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)

                                  POWER OF 10 APPLICABLE TO YD=    0
        YD=      0.0      1.000     2.000    3.000     4.000     5.000     6.000    7.000     8.000     9.000

                                  POWER OF 10 APPLICABLE TO XD=   -2
  XD=    0       0.0    *******   -1.732    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         1     -0.000    -1.132   -1.732    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         2     -0.000    -1.132   -1.732    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         3     -0.000    -1.132   -1.732    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         4     -0.001    -1.132   -1.732    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         5     -0.001    -1.133   -1.732    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         6     -0.002    -1.133   -1.732    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         7     -0.002    -1.133   -1.733    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         8     -0.003    -1.134   -1.733    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         9     -0.004    -1.134   -1.733    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199

                                  POWER OF 10 APPLICABLE TO XD=   -1
  XD=    0       0.0    *******   -1.732    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         1     -0.005    -1.134   -1.733    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         2     -0.020    -1.142   -1.736    -2.119    -2.398    -2.617    -2.797   -2.950    -3.082    -3.200
         3     -0.046    -1.154   -1.741    -2.121    -2.399    -2.618    -2.798   -2.950    -3.083    -3.200
         4     -0.082    -1.171   -1.748    -2.124    -2.401    -2.619    -2.799   -2.951    -3.083    -3.200
         5     -0.131    -1.193   -1.757    -2.129    -2.404    -2.621    -2.800   -2.952    -3.084    -3.201
         6     -0.193    -1.219   -1.767    -2.134    -2.407    -2.623    -2.801   -2.953    -3.085    -3.201
         7     -0.270    -1.249   -1.779    -2.141    -2.411    -2.625    -2.803   -2.954    -3.086    -3.202
         8     -0.368    -1.283   -1.793    -2.148    -2.415    -2.628    -2.805   -2.956    -3.087    -3.203
         9     -0.495    -1.319   -1.808    -2.156    -2.420    -2.631    -2.807   -2.957    -3.088    -3.204

                                  POWER OF 10 APPLICABLE TO XD=    0
  XD=    0       0.0    *******   -1.732    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         1    *******    -1.358   -1.825    -2.164    -2.425    -2.635    -2.810   -2.959    -3.090    -3.205
         2     -1.648    -1.785   -2.040    -2.288    -2.503    -2.688    -2.848   -2.988    -3.112    -3.223
         3     -2.079    -2.138   -2.278    -2.445    -2.611    -2.766    -2.906   -3.032    -3.147    -3.251
         4     -2.376    -2.408   -2.493    -2.608    -2.733    -2.858    -2.977   -3.089    -3.192    -3.289
         5     -2.603    -2.623   -2.679    -2.761    -2.856    -2.956    -3.056   -3.153    -3.245    -3.333
         6     -2.787    -2.801   -2.841    -2.901    -2.974    -3.055    -3.138   -3.222    -3.303    -3.382
         7     -2.942    -2.953   -2.982    -3.028    -3.086    -3.151    -3.221   -3.292    -3.364    -3.434
         8     -3.077    -3.085   -3.108    -3.144    -3.190    -3.244    -3.302   -3.364    -3.426    -3.489
         9     -3.195    -3.201   -3.220    -3.248    -3.286    -3.331    -3.381   -3.433    -3.488    -3.544

                                  POWER OF 10 APPLICABLE TO XD=    1
  XD=    0       0.0    *******   -1.732    -2.117    -2.397    -2.616    -2.796   -2.949    -3.082    -3.199
         1     -3.301    -3.306   -3.321    -3.344    -3.376    -3.413    -3.456   -3.502    -3.550    -3.599
         2     -3.995    -3.997   -4.000    -4.006    -4.015    -4.026    -4.039   -4.053    -4.070    -4.088
         3     -4.401    -4.402   -4.403    -4.406    -4.410    -4.415    -4.421   -4.428    -4.435    -4.444
         4     -4.689    -4.689   -4.690    -4.692    -4.694    -4.697    -4.700   -4.704    -4.708    -4.713
         5     -4.912    -4.912   -4.913    -4.914    -4.915    -4.917    -4.919   -4.922    -4.925    -4.928
         6     -5.094    -5.094   -5.095    -5.096    -5.097    -5.098    -5.099   -5.101    -5.103    -5.105
         7     -5.248    -5.249   -5.249    -5.249    -5.250    -5.251    -5.252   -5.253    -5.255    -5.257
         8     -5.382    -5.382   -5.382    -5.383    -5.383    -5.384    -5.385   -5.386    -5.387    -5.388
         9     -5.500    -5.500   -5.500    -5.500    -5.501    -5.501    -5.502   -5.503    -5.504    -5.505
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                                             TABLE 3
                          VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)
                                         POWER OF 10 APPLICABLE TO YD=   0
       YD=        0.0     1.000     2.000    3.000    4.000    5.000    6.000    7.000    8.000    9.000

                                         POWER OF 10 APPLICABLE TO XD=   2
  XD=   0         0.0   *******    -1.732   -2.117   -2.397   -2.616   -2.796   -2.949   -3.082   -3.199
        1      -5.605    -5.605    -5.605   -5.606   -5.606   -5.606   -5.607   -5.608   -5.608   -5.609
        2      -6.298    -6.298    -6.298   -6.298   -6.299   -6.299   -6.299   -6.299   -6.299   -6.299
        3      -6.704    -6.704    -6.704   -6.704   -6.704   -6.704   -6.704   -6.704   -6.704   -6.704
        4      -6.991    -6.991    -6.991   -6.991   -6.992   -6.992   -6.992   -6.992   -6.992   -6.992
        5      -7.215    -7.215    -7.215   -7.215   -7.215   -7.215   -7.215   -7.215   -7.215   -7.215
        6      -7.397    -7.397    -7.397   -7.397   -7.397   -7.397   -7.397   -7.397   -7.397   -7.397
        7      -7.551    -7.551    -7.551   -7.551   -7.551   -7.551   -7.551   -7.551   -7.551   -7.551
        8      -7.685    -7.685    -7.685   -7.685   -7.685   -7.685   -7.685   -7.685   -7.685   -7.685
        9      -7.802    -7.802    -7.802   -7.802   -7.802   -7.802   -7.802   -7.802   -7.802   -7.802

                                         POWER OF 10 APPLICABLE TO XD=   3
  XD=   0         0.0   *******    -1.732   -2.117   -2.397   -2.616   -2.796   -2.949   -3.082   -3.199
        1      -7.908    -7.908    -7.908   -7.908   -7.908   -7.908   -7.908   -7.908   -7.908   -7.908
        2      -8.601    -8.601    -8.601   -8.601   -8.601   -8.601   -8.601   -8.601   -8.601   -8.601
        3      -9.006    -9.006    -9.006   -9.006   -9.006   -9.006   -9.006   -9.006   -9.006   -9.006
        4      -9.294    -9.294    -9.294   -9.294   -9.294   -9.294   -9.294   -9.294   -9.294   -9.294
        5      -9.517    -9.517    -9.517   -9.517   -9.517   -9.517   -9.517   -9.517   -9.517   -9.517
        6      -9.700    -9.700    -9.700   -9.700   -9.700   -9.700   -9.700   -9.700   -9.700   -9.700
        7      -9.854    -9.854    -9.854   -9.854   -9.854   -9.854   -9.854   -9.854   -9.854   -9.854
        8      -9.987    -9.987    -9.987   -9.987   -9.987   -9.987   -9.987   -9.987   -9.987   -9.987
        9     -10.105   -10.105   -10.105  -10.105  -10.105  -10.105  -10.105  -10.105  -10.105  -10.105

                                         POWER OF 10 APPLICABLE TO XD=   4
  XD=   0         0.0   *******    -1.732   -2.117   -2.397   -2.616   -2.796   -2.949   -3.082   -3.199
        1     -10.210   -10.210   -10.210  -10.210  -10.210  -10.210  -10.210  -10.210  -10.210  -10.210
        2     -10.903   -10.903   -10.903  -10.903  -10.903  -10.903  -10.903  -10.903  -10.903  -10.903
        3     -11.309   -11.309   -11.309  -11.309  -11.309  -11.309  -11.309  -11.309  -11.309  -11.309
        4     -11.597   -11.597   -11.597  -11.597  -11.597  -11.597  -11.597  -11.597  -11.597  -11.597
        5     -11.820   -11.820   -11.820  -11.820  -11.820  -11.820  -11.820  -11.820  -11.820  -11.820
        6     -12.002   -12.002   -12.002  -12.002  -12.002  -12.002  -12.002  -12.002  -12.002  -12.002
        7     -12.156   -12.156   -12.156  -12.156  -12.156  -12.156  -12.156  -12.156  -12.156  -12.156
        8     -12.290   -12.290   -12.290  -12.290  -12.290  -12.290  -12.290  -12.290  -12.290  -12.290
        9     -12.408   -12.408   -12.408  -12.408  -12.408  -12.408  -12.408  -12.408  -12.408  -12.408
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                                              TABLE 3
                          VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)
                                          POWER OF 10 APPLICABLE TO YD=  1
       YD=      0.0      1.000    2.000    3.000    4.000    5.000    6.000    7.000    8.000    9.000

                                          POWER OF 10 APPLICABLE TO XD=  -2
 XD=    0       0.0     -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        1      -0.000   -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        2      -0.000   -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        3      -0.000   -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        4      -0.001   -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        5      -0.001   -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        6      -0.002   -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        7      -0.002   -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        8      -0.003   -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        9      -0.004   -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500

                                          POWER OF 10 APPLICABLE TO XD=  -1
 XD=    0       0.0     -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        1      -0.005   -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        2      -0.020   -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        3      -0.046   -3.305   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        4      -0.082   -3.305   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        5      -0.131   -3.305   -3.996   -4.402   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        6      -0.193   -3.306   -3.997   -4.402   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        7      -0.270   -3.307   -3.997   -4.402   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        8      -0.368   -3.307   -3.997   -4.402   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        9      -0.495   -3.308   -3.997   -4.402   -4.689   -4.912   -5.095   -5.249   -5.382   -5.500

                                          POWER OF 10 APPLICABLE TO XD=   0
 XD=    0       0.0     -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        1     *******   -3.309   -3.997   -4.402   -4.689   -4.912   -5.095   -5.249   -5.382   -5.500
        2      -1.648   -3.324   -4.001   -4.404   -4.690   -4.913   -5.095   -5.249   -5.382   -5.500
        3      -2.079   -3.347   -4.007   -4.406   -4.692   -4.914   -5.096   -5.249   -5.383   -5.500
        4      -2.376   -3.378   -4.016   -4.410   -4.694   -4.915   -5.097   -5.250   -5.383   -5.501
        5      -2.603   -3.415   -4.026   -4.415   -4.697   -4.917   -5.098   -5.251   -5.384   -5.501
        6      -2.787   -3.457   -4.039   -4.421   -4.700   -4.919   -5.099   -5.252   -5.385   -5.502
        7      -2.942   -3.502   -4.054   -4.428   -4.704   -4.922   -5.101   -5.254   -5.386   -5.503
        8      -3.077   -3.550   -4.070   -4.436   -4.709   -4.925   -5.103   -5.255   -5.387   -5.504
        9      -3.195   -3.599   -4.088   -4.444   -4.714   -4.928   -5.106   -5.257   -5.388   -5.505

                                          POWER OF 10 APPLICABLE TO XD=   1
 XD=    0       0.0     -3.304   -3.996   -4.401   -4.689   -4.912   -5.094   -5.249   -5.382   -5.500
        1      -3.301   -3.649   -4.108   -4.454   -4.719   -4.932   -5.108   -5.259   -5.390   -5.506
        2      -3.995   -4.107   -4.342   -4.585   -4.801   -4.986   -5.147   -5.288   -5.412   -5.524
        3      -4.401   -4.454   -4.585   -4.748   -4.912   -5.066   -5.206   -5.333   -5.448   -5.553
        4      -4.689   -4.719   -4.800   -4.912   -5.035   -5.159   -5.278   -5.390   -5.494   -5.590
        5      -4.912   -4.932   -4.986   -5.066   -5.159   -5.259   -5.358   -5.455   -5.547   -5.634
        6      -5.094   -5.108   -5.147   -5.206   -5.278   -5.358   -5.441   -5.524   -5.605   -5.684
        7      -5.248   -5.259   -5.288   -5.333   -5.390   -5.455   -5.524   -5.595   -5.666   -5.736
        8      -5.382   -5.390   -5.412   -5.448   -5.494   -5.547   -5.605   -5.666   -5.729   -5.791
        9      -5.500   -5.506   -5.524   -5.552   -5.590   -5.634   -5.684   -5.736   -5.791   -5.846
```

TABLE 3
VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)

```
                                       POWER OF 10 APPLICABLE TO YD=  1
     YD=       0.0     1.000     2.000     3.000     4.000     5.000     6.000     7.000     8.000     9.000

                                       POWER OF 10 APPLICABLE TO XD=  2
XD=   0        0.0    -3.304    -3.996    -4.401    -4.689    -4.912    -5.094    -5.249    -5.382    -5.500
      1     -5.605    -5.610    -5.625    -5.648    -5.679    -5.717    -5.759    -5.805    -5.853    -5.902
      2     -6.298    -6.300    -6.303    -6.309    -6.318    -6.329    -6.341    -6.356    -6.373    -6.391
      3     -6.704    -6.704    -6.706    -6.709    -6.713    -6.717    -6.723    -6.730    -6.738    -6.747
      4     -6.991    -6.992    -6.993    -6.994    -6.996    -6.999    -7.003    -7.007    -7.011    -7.016
      5     -7.215    -7.215    -7.215    -7.216    -7.218    -7.220    -7.222    -7.224    -7.227    -7.231
      6     -7.397    -7.397    -7.397    -7.398    -7.399    -7.400    -7.402    -7.404    -7.406    -7.408
      7     -7.551    -7.551    -7.551    -7.552    -7.553    -7.554    -7.555    -7.556    -7.558    -7.559
      8     -7.685    -7.685    -7.685    -7.685    -7.686    -7.687    -7.687    -7.688    -7.690    -7.691
      9     -7.802    -7.802    -7.803    -7.803    -7.803    -7.804    -7.805    -7.805    -7.806    -7.807

                                       POWER OF 10 APPLICABLE TO XD=  3
XD=   0        0.0    -3.304    -3.996    -4.401    -4.689    -4.912    -5.094    -5.249    -5.382    -5.500
      1     -7.908    -7.908    -7.908    -7.908    -7.909    -7.909    -7.910    -7.910    -7.911    -7.912
      2     -8.601    -8.601    -8.601    -8.601    -8.601    -8.601    -8.601    -8.602    -8.602    -8.602
      3     -9.006    -9.006    -9.006    -9.006    -9.006    -9.007    -9.007    -9.007    -9.007    -9.007
      4     -9.294    -9.294    -9.294    -9.294    -9.294    -9.294    -9.294    -9.294    -9.294    -9.294
      5     -9.517    -9.517    -9.517    -9.517    -9.517    -9.517    -9.517    -9.517    -9.517    -9.517
      6     -9.700    -9.700    -9.700    -9.700    -9.700    -9.700    -9.700    -9.700    -9.700    -9.700
      7     -9.854    -9.854    -9.854    -9.854    -9.854    -9.854    -9.854    -9.854    -9.854    -9.854
      8     -9.987    -9.987    -9.987    -9.987    -9.987    -9.987    -9.987    -9.987    -9.987    -9.987
      9    -10.105   -10.105   -10.105   -10.105   -10.105   -10.105   -10.105   -10.105   -10.105   -10.105

                                       POWER OF 10 APPLICABLE TO XD=  4
XD=   0        0.0    -3.304    -3.996    -4.401    -4.689    -4.912    -5.094    -5.249    -5.382    -5.500
      1    -10.210   -10.210   -10.210   -10.210   -10.210   -10.210   -10.210   -10.210   -10.210   -10.210
      2    -10.903   -10.903   -10.903   -10.903   -10.903   -10.903   -10.903   -10.903   -10.903   -10.903
      3    -11.309   -11.309   -11.309   -11.309   -11.309   -11.309   -11.309   -11.309   -11.309   -11.309
      4    -11.597   -11.597   -11.597   -11.597   -11.597   -11.597   -11.597   -11.597   -11.597   -11.597
      5    -11.820   -11.820   -11.820   -11.820   -11.820   -11.820   -11.820   -11.820   -11.820   -11.820
      6    -12.002   -12.002   -12.002   -12.002   -12.002   -12.002   -12.002   -12.002   -12.002   -12.002
      7    -12.156   -12.156   -12.156   -12.156   -12.156   -12.156   -12.156   -12.156   -12.156   -12.156
      8    -12.290   -12.290   -12.290   -12.290   -12.290   -12.290   -12.290   -12.290   -12.290   -12.290
      9    -12.408   -12.408   -12.408   -12.408   -12.408   -12.408   -12.408   -12.408   -12.408   -12.408
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                                          TABLE 3
                         VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)
                                            POWER OF 10 APPLICABLE TO YD=   2
         YD=       0.0       1.000     2.000     3.000     4.000     5.000     6.000     7.000     8.000     9.000

                                            POWER OF 10 APPLICABLE TO XD=  -2
   XD=    0        0.0      -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          1       -0.000    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          2       -0.000    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          3       -0.000    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          4       -0.001    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          5       -0.001    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          6       -0.002    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          7       -0.002    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          8       -0.003    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          9       -0.004    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802

                                            POWER OF 10 APPLICABLE TO XD=  -1
   XD=    0        0.0      -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          1       -0.005    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          2       -0.020    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          3       -0.046    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          4       -0.082    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          5       -0.131    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          6       -0.193    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          7       -0.270    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          8       -0.368    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          9       -0.495    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802

                                            POWER OF 10 APPLICABLE TO XD=   0
   XD=    0        0.0      -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          1      *******    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          2       -1.648    -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          3       -2.079    -5.606    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          4       -2.376    -5.606    -6.299    -6.704    -6.992    -7.215    -7.397    -7.551    -7.685    -7.802
          5       -2.603    -5.606    -6.299    -6.704    -6.992    -7.215    -7.397    -7.551    -7.685    -7.802
          6       -2.787    -5.607    -6.299    -6.704    -6.992    -7.215    -7.397    -7.551    -7.685    -7.802
          7       -2.942    -5.608    -6.299    -6.704    -6.992    -7.215    -7.397    -7.551    -7.685    -7.802
          8       -3.077    -5.608    -6.299    -6.704    -6.992    -7.215    -7.397    -7.551    -7.685    -7.802
          9       -3.195    -5.609    -6.299    -6.704    -6.992    -7.215    -7.397    -7.551    -7.685    -7.802

                                            POWER OF 10 APPLICABLE TO XD=   1
   XD=    0        0.0      -5.605    -6.298    -6.704    -6.991    -7.215    -7.397    -7.551    -7.685    -7.802
          1       -3.301    -5.610    -6.300    -6.704    -6.992    -7.215    -7.397    -7.551    -7.685    -7.802
          2       -3.995    -5.625    -6.303    -6.706    -6.993    -7.215    -7.397    -7.551    -7.685    -7.803
          3       -4.401    -5.648    -6.309    -6.709    -6.994    -7.216    -7.398    -7.552    -7.685    -7.803
          4       -4.689    -5.679    -6.318    -6.713    -6.996    -7.218    -7.399    -7.553    -7.686    -7.803
          5       -4.912    -5.717    -6.329    -6.717    -6.999    -7.220    -7.400    -7.554    -7.687    -7.804
          6       -5.094    -5.759    -6.341    -6.723    -7.003    -7.222    -7.402    -7.555    -7.687    -7.805
          7       -5.248    -5.805    -6.356    -6.730    -7.007    -7.224    -7.404    -7.556    -7.688    -7.805
          8       -5.382    -5.853    -6.373    -6.738    -7.011    -7.227    -7.406    -7.558    -7.690    -7.806
          9       -5.500    -5.902    -6.391    -6.747    -7.016    -7.231    -7.408    -7.559    -7.691    -7.807
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                                       TABLE 3
                      VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)

                                        POWER OF 10 APPLICABLE TO YD=   2
         YD=      0.0    1.000    2.000    3.000    4.000    5.000    6.000    7.000    8.000    9.000

                                        POWER OF 10 APPLICABLE TO XD=   2
   XD=   0        0.0   -5.605   -6.298   -6.704   -6.991   -7.215   -7.397   -7.551   -7.685   -7.802
         1     -5.605   -5.952   -6.410   -6.756   -7.022   -7.234   -7.411   -7.561   -7.692   -7.809
         2     -6.298   -6.410   -6.645   -6.888   -7.103   -7.289   -7.450   -7.590   -7.715   -7.826
         3     -6.704   -6.756   -6.888   -7.050   -7.215   -7.368   -7.509   -7.635   -7.750   -7.855
         4     -6.991   -7.022   -7.103   -7.215   -7.338   -7.462   -7.581   -7.692   -7.796   -7.893
         5     -7.215   -7.234   -7.289   -7.368   -7.462   -7.561   -7.661   -7.757   -7.849   -7.937
         6     -7.397   -7.411   -7.450   -7.509   -7.581   -7.661   -7.744   -7.826   -7.908   -7.986
         7     -7.551   -7.561   -7.590   -7.635   -7.692   -7.757   -7.826   -7.898   -7.969   -8.039
         8     -7.685   -7.692   -7.715   -7.750   -7.796   -7.849   -7.908   -7.969   -8.031   -8.094
         9     -7.802   -7.809   -7.826   -7.855   -7.893   -7.937   -7.986   -8.039   -8.094   -8.149

                                        POWER OF 10 APPLICABLE TO XD=   3
   XD=   0        0.0   -5.605   -6.298   -6.704   -6.991   -7.215   -7.397   -7.551   -7.685   -7.802
         1     -7.908   -7.913   -7.927   -7.951   -7.932   -8.019   -8.061   -8.107   -8.155   -8.204
         2     -8.601   -8.602   -8.606   -8.612   -8.621   -8.631   -8.644   -8.659   -8.675   -8.693
         3     -9.006   -9.007   -9.009   -9.011   -9.015   -9.020   -9.026   -9.033   -9.041   -9.049
         4     -9.294   -9.294   -9.295   -9.297   -9.299   -9.302   -9.305   -9.309   -9.314   -9.319
         5     -9.517   -9.517   -9.518   -9.519   -9.520   -9.522   -9.524   -9.527   -9.530   -9.533
         6     -9.700   -9.700   -9.700   -9.701   -9.702   -9.703   -9.704   -9.706   -9.708   -9.711
         7     -9.854   -9.854   -9.854   -9.855   -9.855   -9.856   -9.857   -9.859   -9.860   -9.862
         8     -9.987   -9.987   -9.988   -9.988   -9.988   -9.989   -9.990   -9.991   -9.992   -9.993
         9    -10.105  -10.105  -10.105  -10.106  -10.106  -10.107  -10.107  -10.108  -10.109  -10.110

                                        POWER OF 10 APPLICABLE TO XD=   4
   XD=   0        0.0   -5.605   -6.298   -6.704   -6.991   -7.215   -7.397   -7.551   -7.685   -7.802
         1    -10.210  -10.210  -10.211  -10.211  -10.211  -10.212  -10.212  -10.213  -10.214  -10.214
         2    -10.903  -10.904  -10.904  -10.904  -10.904  -10.904  -10.904  -10.904  -10.904  -10.904
         3    -11.309  -11.309  -11.309  -11.309  -11.309  -11.309  -11.309  -11.309  -11.309  -11.309
         4    -11.597  -11.597  -11.597  -11.597  -11.597  -11.597  -11.597  -11.597  -11.597  -11.597
         5    -11.820  -11.820  -11.820  -11.820  -11.820  -11.820  -11.820  -11.820  -11.820  -11.820
         6    -12.002  -12.002  -12.002  -12.002  -12.002  -12.002  -12.002  -12.002  -12.002  -12.002
         7    -12.156  -12.156  -12.156  -12.156  -12.156  -12.156  -12.156  -12.156  -12.156  -12.156
         8    -12.290  -12.290  -12.290  -12.290  -12.290  -12.290  -12.290  -12.290  -12.290  -12.290
         9    -12.408  -12.408  -12.408  -12.408  -12.408  -12.408  -12.408  -12.408  -12.408  -12.408
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                                      TABLE 3
                    VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)

                                   POWER OF 10 APPLICABLE TO YD=   3
        YD=       0.0       1.000     2.000    3.000    4.000    5.000    6.000    7.000     8.000     9.000

                                   POWER OF 10 APPLICABLE TO XD=  -2
   XD=   0        0.0      -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         1       -0.000    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         2       -0.000    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         3       -0.000    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         4       -0.001    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         5       -0.001    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         6       -0.002    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         7       -0.002    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         8       -0.003    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         9       -0.004    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105

                                   POWER OF 10 APPLICABLE TO XD=  -1
   XD=   0        0.0      -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         1       -0.005    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         2       -0.020    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         3       -0.046    -7.909    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         4       -0.082    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         5       -0.131    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         6       -0.193    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         7       -0.270    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         8       -0.368    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         9       -0.495    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105

                                   POWER OF 10 APPLICABLE TO XD=   0
   XD=   0        0.0      -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         1      ********   -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         2       -1.648    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         3       -2.079    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         4       -2.376    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         5       -2.603    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         6       -2.787    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         7       -2.942    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         8       -3.077    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         9       -3.195    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105

                                   POWER OF 10 APPLICABLE TO XD=   1
   XD=   0        0.0      -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         1       -3.301    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         2       -3.995    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         3       -4.401    -7.908    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         4       -4.689    -7.909    -8.601   -9.006   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         5       -4.912    -7.909    -8.601   -9.007   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         6       -5.094    -7.910    -8.601   -9.007   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         7       -5.248    -7.910    -8.602   -9.007   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         8       -5.382    -7.911    -8.602   -9.007   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
         9       -5.500    -7.912    -8.602   -9.007   -9.294   -9.517   -9.700   -9.854    -9.987  -10.105
```

TABLE 3
VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)

```
                                 POWER OF 10 APPLICABLE TO YD=   3
     YD=       0.0      1.000    2.000    3.000    4.000    5.000    6.000    7.000    8.000    9.000

                                 POWER OF 10 APPLICABLE TO XD=   2
XD=     0      0.0     -7.908   -8.601   -9.006   -9.294   -9.517   -9.700   -9.854   -9.987 -10.105
        1     -5.605   -7.913   -8.602   -9.007   -9.294   -9.517   -9.700   -9.854   -9.987 -10.105
        2     -6.298   -7.927   -8.606   -9.009   -9.295   -9.518   -9.700   -9.854   -9.988 -10.105
        3     -6.704   -7.951   -8.612   -9.011   -9.297   -9.519   -9.701   -9.855   -9.988 -10.106
        4     -6.991   -7.982   -8.621   -9.015   -9.299   -9.520   -9.702   -9.855   -9.988 -10.106
        5     -7.215   -8.019   -8.631   -9.020   -9.302   -9.522   -9.703   -9.856   -9.989 -10.107
        6     -7.397   -8.061   -8.644   -9.026   -9.305   -9.524   -9.704   -9.857   -9.990 -10.107
        7     -7.551   -8.107   -8.659   -9.033   -9.309   -9.527   -9.706   -9.859   -9.991 -10.108
        8     -7.685   -8.155   -8.675   -9.041   -9.314   -9.530   -9.708   -9.860   -9.992 -10.109
        9     -7.802   -8.204   -8.693   -9.049   -9.319   -9.533   -9.711   -9.862   -9.993 -10.110

                                 POWER OF 10 APPLICABLE TO XD=   3
XD=     0      0.0     -7.908   -8.601   -9.006   -9.294   -9.517   -9.700   -9.854   -9.987 -10.105
        1     -7.908   -8.254   -8.712   -9.059   -9.324   -9.537   -9.713   -9.864   -9.995 -10.111
        2     -8.601   -8.712   -8.947   -9.190   -9.406   -9.591   -9.752   -9.893 -10.018 -10.129
        3     -9.006   -9.059   -9.190   -9.353   -9.517   -9.671   -9.811   -9.938 -10.053 -10.158
        4     -9.294   -9.324   -9.406   -9.517   -9.641   -9.765   -9.883   -9.995 -10.099 -10.195
        5     -9.517   -9.537   -9.591   -9.671   -9.765   -9.864   -9.963 -10.060 -10.152 -10.239
        6     -9.700   -9.713   -9.752   -9.811   -9.883   -9.963 -10.046 -10.129 -10.210 -10.289
        7     -9.854   -9.864   -9.893   -9.938   -9.995 -10.060 -10.129 -10.200 -10.271 -10.342
        8     -9.987   -9.995 -10.018 -10.053 -10.099 -10.152 -10.210 -10.271 -10.334 -10.396
        9    -10.105 -10.111 -10.129 -10.158 -10.195 -10.239 -10.289 -10.342 -10.396 -10.452

                                 POWER OF 10 APPLICABLE TO XD=   4
XD=     0      0.0     -7.908   -8.601   -9.006   -9.294   -9.517   -9.700   -9.854   -9.987 -10.105
        1    -10.210 -10.215 -10.230 -10.253 -10.285 -10.322 -10.364 -10.410 -10.458 -10.507
        2    -10.903 -10.905 -10.908 -10.915 -10.923 -10.934 -10.947 -10.961 -10.978 -10.996
        3    -11.309 -11.310 -11.311 -11.314 -11.318 -11.323 -11.329 -11.335 -11.343 -11.352
        4    -11.597 -11.597 -11.598 -11.599 -11.602 -11.604 -11.608 -11.612 -11.616 -11.621
        5    -11.820 -11.820 -11.821 -11.822 -11.823 -11.825 -11.827 -11.829 -11.832 -11.836
        6    -12.002 -12.002 -12.003 -12.003 -12.004 -12.006 -12.007 -12.009 -12.011 -12.013
        7    -12.156 -12.156 -12.157 -12.157 -12.158 -12.159 -12.160 -12.161 -12.163 -12.164
        8    -12.290 -12.290 -12.290 -12.290 -12.291 -12.292 -12.293 -12.294 -12.295 -12.296
        9    -12.408 -12.408 -12.408 -12.408 -12.409 -12.409 -12.410 -12.411 -12.412 -12.413
```

```
                                        TABLE 3
                     VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)

                                         POWER OF 10 APPLICABLE TO YD=   4
         YD=       0.0       1.000   2.000   3.000   4.000   5.000   6.000   7.000   8.000   9.000

                                         POWER OF 10 APPLICABLE TO XD=  -2
   XD=    0       0.0    -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          1      -0.000  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          2      -0.000  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          3      -0.000  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          4      -0.001  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          5      -0.001  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          6      -0.002  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          7      -0.002  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          8      -0.003  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          9      -0.004  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408

                                         POWER OF 10 APPLICABLE TO XD=  -1
   XD=    0       0.0    -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          1      -0.005  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          2      -0.020  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          3      -0.046  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          4      -0.082  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          5      -0.131  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          6      -0.193  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          7      -0.270  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          8      -0.368  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          9      -0.495  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408

                                         POWER OF 10 APPLICABLE TO XD=   0
   XD=    0       0.0    -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          1     *******  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          2      -1.648  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          3      -2.079  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          4      -2.376  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          5      -2.603  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          6      -2.787  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          7      -2.942  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          8      -3.077  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          9      -3.195  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408

                                         POWER OF 10 APPLICABLE TO XD=   1
   XD=    0       0.0    -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          1      -3.301  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          2      -3.995  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          3      -4.401  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          4      -4.689  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          5      -4.912  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          6      -5.094  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          7      -5.248  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          8      -5.382  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
          9      -5.500  -10.210 -10.903 -11.309 -11.597 -11.820 -12.002 -12.156 -12.290 -12.408
```

TABLE 3
VALUES OF SIGMA (PSEUDO SKIN, VERTICAL FRACTURE)

```
     YD=        0.0      1.000    2.000  POWER OF 10 APPLICABLE TC YD=   4
                                          3.000    4.000    5.000    6.000    7.000    8.000    9.000
XD=    0                                 POWER OF 10 APPLICABLE TO XD=    2
                0.0     -10.210  -10.903  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       1       -5.605   -10.210  -10.904  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       2       -6.298   -10.211  -10.904  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       3       -6.704   -10.211  -10.904  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       4       -6.991   -10.211  -10.904  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       5       -7.215   -10.212  -10.904  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       6       -7.397   -10.212  -10.904  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       7       -7.551   -10.213  -10.904  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       8       -7.685   -10.214  -10.904  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       9       -7.802   -10.214  -10.904  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408

XD=    0                                 POWER OF 10 APPLICABLE TO XD=    3
                0.0     -10.210  -10.903  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       1       -7.908   -10.215  -10.905  -11.310  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       2       -8.601   -10.230  -10.908  -11.311  -11.598  -11.821  -12.003  -12.156  -12.290  -12.408
       3       -9.006   -10.253  -10.915  -11.314  -11.599  -11.822  -12.003  -12.157  -12.290  -12.408
       4       -9.294   -10.285  -10.923  -11.318  -11.602  -11.823  -12.004  -12.157  -12.290  -12.408
       5       -9.517   -10.322  -10.934  -11.323  -11.604  -11.825  -12.006  -12.158  -12.291  -12.409
       6       -9.700   -10.364  -10.947  -11.329  -11.608  -11.827  -12.007  -12.159  -12.292  -12.409
       7       -9.854   -10.410  -10.961  -11.335  -11.612  -11.829  -12.009  -12.160  -12.293  -12.410
       8       -9.987   -10.458  -10.978  -11.343  -11.616  -11.832  -12.011  -12.161  -12.294  -12.411
       9      -10.105   -10.507  -10.996  -11.352  -11.621  -11.836  -12.013  -12.163  -12.295  -12.412
                                                                                 -12.164  -12.296  -12.413

XD=    0                                 POWER OF 10 APPLICABLE TO XD=    4
                0.0     -10.210  -10.903  -11.309  -11.597  -11.820  -12.002  -12.156  -12.290  -12.408
       1      -10.210   -10.557  -11.015  -11.362  -11.627  -11.839  -12.016  -12.166  -12.298  -12.414
       2      -10.903   -11.015  -11.250  -11.493  -11.708  -11.894  -12.055  -12.195  -12.320  -12.432
       3      -11.309   -11.362  -11.493  -11.656  -11.820  -11.974  -12.114  -12.241  -12.356  -12.460
       4      -11.597   -11.627  -11.708  -11.820  -11.943  -12.067  -12.186  -12.298  -12.401  -12.498
       5      -11.820   -11.839  -11.894  -11.974  -12.067  -12.166  -12.266  -12.362  -12.455  -12.542
       6      -12.002   -12.016  -12.055  -12.114  -12.186  -12.266  -12.349  -12.432  -12.513  -12.591
       7      -12.156   -12.166  -12.195  -12.241  -12.298  -12.362  -12.432  -12.503  -12.574  -12.644
       8      -12.290   -12.298  -12.320  -12.356  -12.401  -12.455  -12.513  -12.574  -12.636  -12.699
       9      -12.408   -12.414  -12.432  -12.460  -12.498  -12.542  -12.591  -12.644  -12.699  -12.754
```

TABLE 4
VALUES OF PD WITH CAPROCK LEAKAGE

```
       TD=       1.0000  2.0000  3.0000  4.0000  5.0000  6.0000  7.0000  8.0000  9.0000

                                 POWER OF 10 =   -1 (APPLIES TO TD ONLY)
R/B=   0.02      0.0124  0.0732  0.1428  0.2135  0.2779  0.3359  0.3885  0.4365  0.4804
       0.04      0.0124  0.0732  0.1458  0.2157  0.2795  0.3372  0.3896  0.4373  0.4812
       0.06      0.0124  0.0732  0.1458  0.2156  0.2794  0.3370  0.3893  0.4370  0.4807
       0.08      0.0124  0.0732  0.1460  0.2157  0.2793  0.3369  0.3890  0.4366  0.4802
       0.10      0.0124  0.0731  0.1460  0.2156  0.2791  0.3365  0.3885  0.4360  0.4795
       0.20      0.0124  0.0728  0.1451  0.2140  0.2766  0.3331  0.3842  0.4306  0.4730
       0.30      0.0124  0.0723  0.1437  0.2114  0.2727  0.3276  0.3770  0.4217  0.4623
       0.40      0.0123  0.0717  0.1418  0.2078  0.2672  0.3200  0.3673  0.4097  0.4480
       0.50      0.0122  0.0709  0.1393  0.2033  0.2603  0.3106  0.3552  0.3949  0.4303
       0.60      0.0121  0.0698  0.1363  0.1979  0.2522  0.2996  0.3410  0.3775  0.4098
       0.70      0.0120  0.0686  0.1329  0.1917  0.2429  0.2870  0.3252  0.3583  0.3872
       0.80      0.0119  0.0673  0.1290  0.1849  0.2327  0.2733  0.3079  0.3375  0.3630
       0.90      0.0117  0.0659  0.1246  0.1772  0.2216  0.2586  0.2896  0.3156  0.3377
       1.00      0.0115  0.0642  0.1197  0.1690  0.2097  0.2431  0.2704  0.2931  0.3118

                                 POWER OF 10 =    0 (APPLIES TO TD ONLY)
R/B=   0.02      0.5210  0.8109  0.9939  1.1276  1.2329  1.3199  1.3938  1.4582  1.5152
       0.04      0.5216  0.8106  0.9928  1.1259  1.2306  1.3170  1.3903  1.4542  1.5106
       0.06      0.5211  0.8092  0.9906  1.1227  1.2265  1.3119  1.3844  1.4472  1.5027
       0.08      0.5205  0.8074  0.9875  1.1183  1.2208  1.3049  1.3760  1.4376  1.4918
       0.10      0.5196  0.8050  0.9834  1.1127  1.2135  1.2960  1.3655  1.4254  1.4779
       0.20      0.5119  0.7852  0.9509  1.0673  1.1555  1.2255  1.2827  1.3305  1.3712
       0.30      0.4995  0.7537  0.9002  0.9981  1.0686  1.1217  1.1631  1.1960  1.2227
       0.40      0.4827  0.7125  0.8358  0.9126  0.9642  1.0004  1.0267  1.0462  1.0609
       0.50      0.4622  0.6641  0.7630  0.8193  0.8537  0.8759  0.8906  0.9005  0.9074
       0.60      0.4386  0.6111  0.6867  0.7252  0.7464  0.7585  0.7657  0.7702  0.7728
       0.70      0.4126  0.5561  0.6112  0.6359  0.6477  0.6538  0.6567  0.6584  0.6593
       0.80      0.3850  0.5012  0.5396  0.5542  0.5603  0.5629  0.5641  0.5647  0.5649
       0.90      0.3564  0.4481  0.4735  0.4817  0.4846  0.4857  0.4861  0.4862  0.4863
       1.00      0.3275  0.3980  0.4141  0.4184  0.4197  0.4201  0.4202  0.4202  0.4202

                                 POWER OF 10 =    1 (APPLIES TO TD ONLY)
R/B=   0.02      1.5664  1.9048  2.1035  2.2444  2.3534  2.4421  2.5170  2.5815  2.6383
       0.04      1.5611  1.8937  2.0866  2.2217  2.3250  2.4081  2.4773  2.5363  2.5876
       0.06      1.5523  1.8754  2.0590  2.1851  2.2795  2.3540  2.4148  2.4656  2.5088
       0.08      1.5400  1.8504  2.0218  2.1362  2.2195  2.2833  2.3340  2.3753  2.4094
       0.10      1.5246  1.8193  1.9762  2.0771  2.1480  2.2005  2.2406  2.2721  2.2972
       0.20      1.4063  1.5987  1.6740  1.7098  1.7284  1.7386  1.7444  1.7477  1.7496
       0.30      1.2445  1.3404  1.3630  1.3694  1.3714  1.3721  1.3723  1.3724  1.3724
       0.40      1.0722  1.1095  1.1133  1.1144  1.1145  1.1145  1.1145  1.1145  1.1145
       0.50      0.9122  0.9233  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244
       0.60      0.7745  0.7774  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775
       0.70      0.6593  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604
       0.80      0.5650  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652
       0.90      0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863
       1.00      0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202
```

TABLE 4
VALUES OF PD WITH CAPROCK LEAKAGE

```
        TD=     1.0000  2.0000  3.0000  4.0000  5.0000  6.0000  7.0000  8.0000  9.0000

                                POWER OF 10 =    2 (APPLIES TO TD ONLY)
R/B=    0.02    2.6889  3.0155  3.1990  3.3241  3.4173  3.4905  3.5499  3.5994  3.6413
        0.04    2.6327  2.9077  3.0443  3.1268  3.1813  3.2192  3.2465  3.2667  3.2819
        0.06    2.5462  2.7531  2.8369  2.8782  2.9006  2.9133  2.9208  2.9254  2.9281
        0.08    2.4380  2.5777  2.6202  2.6360  2.6424  2.6452  2.6464  2.6470  2.6473
        0.10    2.3176  2.4026  2.4206  2.4252  2.4265  2.4269  2.4270  2.4271  2.4271
        0.20    1.7508  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527
        0.30    1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725
        0.40    1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145
        0.50    0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244
        0.60    0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775
        0.70    0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604
        0.80    0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652
        0.90    0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863
        1.00    0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202

                                POWER OF 10 =    3 (APPLIES TO TD ONLY)
R/B=    0.02    3.6773  3.8732  3.9493  3.9853  4.0041  4.0143  4.0201  4.0234  4.0254
        0.04    3.2934  3.3315  3.3358  3.3364  3.3365  3.3365  3.3366  3.3366  3.3366
        0.06    2.9298  2.9328  2.9329  2.9329  2.9329  2.9329  2.9329  2.9329  2.9329
        0.08    2.6474  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475
        0.10    2.4271  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271
        0.20    1.7527  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527
        0.30    1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725
        0.40    1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145
        0.50    0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244
        0.60    0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775
        0.70    0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604
        0.80    0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652
        0.90    0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863
        1.00    0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202

                                POWER OF 10 =    4 (APPLIES TO TD ONLY)
R/B=    0.02    4.0266  4.0284  4.0285  4.0285  4.0285  4.0285  4.0285  4.0285  4.0285
        0.04    3.3366  3.3366  3.3366  3.3366  3.3366  3.3366  3.3366  3.3366  3.3366
        0.06    2.9329  2.9329  2.9329  2.9329  2.9329  2.9329  2.9329  2.9329  2.9329
        0.08    2.6475  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475
        0.10    2.4271  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271
        0.20    1.7527  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527
        0.30    1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725
        0.40    1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145
        0.50    0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244
        0.60    0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775
        0.70    0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604
        0.80    0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652
        0.90    0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863
        1.00    0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202
```

```
                                              TABLE 4
                              VALUES OF PD WITH CAPROCK LEAKAGE
       TD=      1.0000  2.0000  3.0000  4.0000  5.0000  6.0000  7.0000  8.0000  9.0000

R/B=  0.02      4.0285  4.0285  POWER OF 10 =   5 (APPLIES TO TD ONLY)
      0.04      3.3366  3.3366  4.0285  4.0285  4.0285  4.0285  4.0285  4.0285  4.0285
      0.06      2.9329  2.9329  3.3366  3.3366  3.3366  3.3366  3.3366  3.3366  3.3366
      0.08      2.6475  2.6475  2.9329  2.9329  2.9329  2.9329  2.9329  2.9329  2.9329
      0.10      2.4271  2.4271  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475
      0.20      1.7527  1.7527  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271
      0.30      1.3725  1.3725  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527
      0.40      1.1145  1.1145  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725
      0.50      0.9244  0.9244  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145
      0.60      0.7775  0.7775  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244
      0.70      0.6604  0.6604  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775
      0.80      0.5652  0.5652  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604
      0.90      0.4863  0.4863  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652
      1.00      0.4202  0.4202  0.4863  0.4863  0.4863  0.4363  0.4863  0.4863  0.4863
                                0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202

R/B=  0.02      4.0285  4.0285  POWER OF 10 =   6 (APPLIES TO TD ONLY)
      0.04      3.3366  3.3366  4.0285  4.0285  4.0285  4.0285  4.0285  4.0285  4.0285
      0.06      2.9329  2.9329  3.3366  3.3366  3.3366  3.3366  3.3366  3.3366  3.3366
      0.08      2.6475  2.6475  2.9329  2.9329  2.9329  2.9329  2.9329  2.9329  2.9329
      0.10      2.4271  2.4271  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475
      0.20      1.7527  1.7527  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271
      0.30      1.3725  1.3725  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527
      0.40      1.1145  1.1145  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725
      0.50      0.9244  0.9244  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145
      0.60      0.7775  0.7775  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244
      0.70      0.6604  0.6604  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775
      0.80      0.5652  0.5652  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604
      0.90      0.4863  0.4863  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652
      1.00      0.4202  0.4202  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863
                                0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202

R/B=  0.02      4.0285  4.0285  POWER OF 10 =   7 (APPLIES TO TD ONLY)
      0.04      3.3366  3.3366  4.0285  4.0285  4.0285  4.0285  4.0285  4.0285  4.0285
      0.06      2.9329  2.9329  3.3366  3.3366  3.3366  3.3366  3.3366  3.3366  3.3366
      0.08      2.6475  2.6475  2.9329  2.9329  2.9329  2.9329  2.9329  2.9329  2.9329
      0.10      2.4271  2.4271  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475  2.6475
      0.20      1.7527  1.7527  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271  2.4271
      0.30      1.3725  1.3725  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527  1.7527
      0.40      1.1145  1.1145  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725  1.3725
      0.50      0.9244  0.9244  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145  1.1145
      0.60      0.7775  0.7775  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244  0.9244
      0.70      0.6604  0.6604  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775  0.7775
      0.80      0.5652  0.5652  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604  0.6604
      0.90      0.4363  0.4863  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652  0.5652
      1.00      0.4202  0.4202  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863  0.4863
                                0.4202  0.4202  0.4202  0.4202  0.4202  0.4202  0.4202
```

APPENDIX B

PROGRAMMABLE DESK CALCULATOR PROGRAMS

1. Exponential integral
2. Error function
3. Single or multiple wells, constant injection or pumping rate
4. Single or multiple wells, variable injection or pumping rates
5. Single vertical fracture, wellbore case
6. Single vertical fracture, general case
7. Single horizontal fracture
8. Partially penetrating wells
9. Semiconfined reservoirs

PROGRAM TITLE: Exponential Integral

PARTITIONING: Normal

PROGRAM DESCRIPTION: Evaluates the exponential integral (National Bureau of Standards, 1964), which is a part of numerous pressure buildup solutions.

Program calculates:

$$E_1(x) = \int_x^{\infty} \frac{e^{-u}}{u}\,du = -0.5772 - \ln x - \sum_{n=1}^{\infty} \frac{(-x)^n}{n(n!)}$$

Note: Results are accurate to ± 0.1% for $0 < x \leq 5$.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS		DISPLAY
1	To calculate $E_1(x)$ when only the program for $E_1(x)$ is being used	x	RST	R/S	$E_1(x)$
1	To calculate $E_1(x)$ when any program incorporating $E_1(x)$ as a subroutine is being used	x	RST	R/S	$E_1(x)$

PROGRAM

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
000	42	STO	033	75	-	066	00	0	099	77	2nd x≥t
001	30	30	034	43	RCL	067	72	72	100	01	1
002	53	(	035	00	00	068	22	INV	101	06	06
003	23	ln x	036	54	)	069	86	2nd Stflg	102	97	2nd Dsz
004	85	+	037	42	STO	070	05	5	103	00	0
005	93	.	038	31	31	071	94	+/-	104	00	0
006	05	5	039	53	(	072	53	(	105	30	30
007	07	7	040	43	RCL	073	24	CE	106	43	RCL
008	07	7	041	30	30	074	85	+	107	33	33
009	02	2	042	45	y^x	075	43	RCL	108	94	+/-
010	54	)	043	43	RCL	076	33	33	109	92	INVSBR
011	42	STO	044	31	31	077	54	)			
012	33	33	045	55	÷	078	48	2nd Exc			
013	03	3	046	43	RCL	079	33	33			
014	05	5	047	31	31	080	97	2nd Dsz			
015	42	STO	048	55	÷	081	03	3			
016	00	00	049	53	(	082	01	1			
017	01	1	050	43	RCL	083	02	02			
018	42	STO	051	31	31	084	22	INV			
019	32	32	052	65	x	085	87	2nd Ifflg			
020	06	6	053	43	RCL	086	05	5			
021	42	STO	054	32	32	087	01	1			
022	03	03	055	54	)	088	02	02			
023	93	.	056	42	STO	089	53	(			
024	00	0	057	32	32	090	24	CE			
025	00	0	058	54	)	091	55	÷			
026	01	1	059	87	2nd Ifflg	092	43	RCL			
027	32	x⇄t	060	05	5	093	33	33			
028	86	2nd Stflg	061	00	0	094	75	-			
029	05	5	062	68	68	095	01	1			
030	53	(	063	86	2nd Stflg	096	54	)			
031	03	3	064	05	5	097	50	2nd |x|			
032	06	6	065	61	GTO	098	22	INV			

PROGRAM TITLE: Error Function

PARTITIONING: Normal

PROGRAM DESCRIPTION: Evaluates the error function (National Bureau of Standards, 1964), which is a part of several pressure buildup solutions.

Program calculates:

$$\mathrm{erf}(x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} dt =$$

$$= \frac{2}{\sqrt{\pi}} \sum_{n=0}^{\infty} \frac{(-1)^n x^{2n+1}}{n!(2n+1)}$$

Note: Results are accurate to ± 0.1% for $x \leq 5$.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	To calculate erf(x) when only the program for erf(x) is being used	x	GTO	110	R/S	erf(x)
1	To calculate erf(x) when any program incorporating erf(x) as a subroutine is being used	x	SBR	110		erf(x)

PROGRAM

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
110	42	STO	143	01	1	176	94	+/-	209	28	28
111	34	34	144	54	)	177	22	INV	210	53	(
112	42	STO	145	42	STO	178	86	2nd Stflg	211	43	RCL
113	35	35	146	39	39	179	03	3	212	34	34
114	86	2nd Stflg	147	53	(	180	53	(	213	65	x
115	03	3	148	43	RCL	181	24	CE	214	02	2
116	01	1	149	35	35	182	85	+	215	55	÷
117	42	STO	150	45	y^x	183	43	RCL	216	89	2nd π
118	36	36	151	43	RCL	184	34	34	217	34	$\sqrt{x}$
119	93	.	152	39	39	185	54	)	218	54	)
120	00	0	153	55	÷	186	48	2nd Exc	219	92	**INV SBR**
121	00	0	154	43	RCL	187	34	34			
122	01	1	155	39	39	188	22	INV			
123	32	x⇄t	156	55	÷	189	87	2nd Ifflg			
124	09	9	157	53	(	190	03	3			
125	08	8	158	43	RCL	191	02	2			
126	42	STO	159	38	38	192	06	06			
127	06	06	160	65	x	193	53	(			
128	53	(	161	43	RCL	194	24	CE			
129	09	9	162	36	36	195	55	÷			
130	09	9	163	54	)	196	43	RCL			
131	75	-	164	42	STO	197	34	34			
132	43	RCL	165	36	36	198	75	-			
133	06	06	166	54	)	199	01	1			
134	54	)	167	87	2nd Ifflg	200	54	)			
135	42	STO	168	03	3	201	50	2nd $\lvert x \rvert$			
136	38	38	169	01	1	202	22	INV			
137	53	(	170	76	76	203	77	2nd x≥t			
138	43	RCL	171	86	2nd Stflg	204	02	2			
139	38	38	172	03	3	205	10	10			
140	65	x	173	61	GTO	206	97	2nd Dsz			
141	02	2	174	01	1	207	06	6			
142	85	+	175	80	80	208	01	1			

PROGRAM TITLE: Single or Multiple Wells, Constant Injection or Pumping Rate.

PARTITIONING: Normal

PROGRAM DESCRIPTION: Solves for pressure buildup (decline) at any point in a fully confined infinite reservoir as a result of injection (pumping) at a constant rate into (from) a single completely penetrating well. The program will also calculate the combined effects of multiple wells, where all wells are operating at constant injection or pumping rates and are completely penetrating.

Program calculates:

$$P_r = P_i + \sum_{n=1}^{m} \frac{70.6 q_n \mu_n \beta_n}{kh} \left(E_1 \left(\frac{39.5\ \phi \mu_n c r_n^2}{k t_n} \right) + 2\ S_n \right)$$

where:

E_1 = exponential integral--see exponential integral program

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Enter number of wells	m	A			m
2	Enter initial reservoir pressure	P_i (psi)	B			P_i
3	Enter injection or pumping rate of well n	q_n (STB/D)	C			q_n
4	Enter radial distance from well n to point of investigation	r_n (ft)	D			r_n
5	Enter time since injection into or pumping from well n began	t_n (D)	E			t_n
6	Enter average horizontal reservoir permeability	k (md)	STO	1	4	k
7	Enter reservoir thickness	h (ft)	STO	1	5	h
8	Enter reservoir porosity	ϕ (fraction)	STO	1	6	ϕ
9	Enter viscosity	μ_n (cp)	STO	1	7	μ_n
10	Enter system compressibility	c (1/psi)	STO	1	8	c
11	Enter formation volume factor	β_n (RB/STB)	STO	1	9	β_n
12	Enter skin factor for well n	S_n	STO	2	0	S_n
13	Start execution of calculation		2nd	E'		P_r

NOTE: Calculated pressures are accumulative. For second and subsequent wells enter only data which have changed, then press 2nd E'. If it is desired to restart a series of calculations before m calculations have been made, P_i must be reentered as the original value.

PROGRAM

NOTE: Program steps 000-109 are separately documented as the $E_1(x)$ subroutine. Enter this subroutine, then enter the remaining steps listed here.

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
110	76	2nd Lbl	138	43	RCL	166	14	14	194	00	0
111	11	A	139	10	10	167	54	)	195	93	.
112	42	STO	140	85	+	168	71	SBR	196	06	6
113	05	05	141	53	(	169	00	0	197	54	)
114	91	R/S	142	53	(	170	00	00	198	97	2nd Dsz
115	76	2nd Lbl	143	03	3	171	85	+	199	05	5
116	12	B	144	09	9	172	02	2	200	12	B
117	42	STO	145	93	.	173	65	x	201	92	INV SBR
118	10	10	146	05	5	174	43	RCL			
119	91	R/S	147	01	1	175	20	20			
120	76	2nd Lbl	148	65	x	176	54	)			
121	13	C	149	43	RCL	177	65	x			
122	42	STO	150	16	16	178	43	RCL			
123	11	11	151	65	x	179	11	11			
124	91	R/S	152	43	RCL	180	65	x			
125	76	2nd Lbl	153	17	17	181	43	RCL			
126	14	D	154	65	x	182	17	17			
127	42	STO	155	43	RCL	183	65	x			
128	12	12	156	18	18	184	43	RCL			
129	91	R/S	157	65	x	185	19	19			
130	76	2nd Lbl	158	43	RCL	186	55	÷			
131	15	E	159	12	12	187	43	RCL			
132	42	STO	160	33	x^2	188	14	14			
133	13	13	161	55	÷	189	55	÷			
134	91	R/S	162	43	RCL	190	43	RCL			
135	76	2nd Lbl	163	13	13	191	15	15			
136	10	2nd E'	164	55	÷	192	65	x			
137	53	(	165	43	RCL	193	07	7			

PROGRAM TITLE: Single or Multiple Wells, Variable Injection or Pumping Rates

PARTITIONING: Normal

PROGRAM DESCRIPTION: Solves for pressure buildup (decline) at any point in a fully confined infinite reservoir as a result of injection (pumping) at variable rates into (from) a single completely penetrating well. The program will also calculate the combined effects of multiple completely penetrating wells.

Program calculates:

$$P_r = P_i + \sum_{b=1}^{m} \sum_{a-1}^{n} \frac{70.6\left(q_{ba} - q_{b,a-1}\right)\mu_b \beta_b}{kh} \left(E_1\left(\frac{39.5\phi\mu_b c r_b^2}{k\left(t_b - t_{ba}\right)}\right) + 2s\right)$$

where:

E_1 = exponential integral--see exponential integral program

b = well number

a = rate number of well b

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Enter number of wells	m	GTO	x^2	R/S	0
2	Enter number of injection (pumping) rates for well b under consideration.	n	R/S			n
3	Enter initial reservoir pressure	P_i (psi)	A			P_i
4	Enter injection (pumping) rate of well b at time period a	q_{ba} (STB/D)	B			q_{ba}
5	Enter radial distance from well b to point of investigation	r_b (ft)	C			r_b
6	Enter number of days of injection (pumping) at rate a	t_{ba} (D)	D			t_{ba}
7	Enter total number of days of operation of well b at all rates	t_b (D)	E			t_b
8	Enter average horizontal reservoir permeability	k (md)	STO	1	5	k
9	Enter reservoir thickness	h (ft)	STO	1	6	h
10	Enter reservoir porosity	ϕ (fraction)	STO	1	7	ϕ
11	Enter viscosity	μ_b (cp)	STO	1	8	μ_b
12	Enter system compressibility	C (1/psi)	STO	1	9	C
13	Enter formation volume factor	β (RB/STB)	STO	2	0	β
14	Enter skin factor	S	STO	2	1	S
15	Start execution of calculation		2nd	E'		P_r

NOTE: Pressures are calculated and displayed cumulatively for each rate and for each well. After rate 1 has been calculated for well 1, proceed to rate 2 and time period 2, etc., until all rates for well 1 have been calculated. For well 2, enter the number of rates, then the rates and times for well 2, until all rates and times have been used. A final pressure is displayed after all wells and all rates and time periods have been taken into account. At the end of all rate calculations for all but last well, the calculator will display zero. To read the cumulated pressure, when the display is zero, press RCL 10. If a series of calculations is aborted, and it is desired to begin over, reenter the m,n, and P_i. A value for m,n and P_i must be entered for each new series of calculations, even though the numbers may be the same as for the previous series of calculations.

PROGRAM

NOTE: Program steps 000-109 are separately documented as the $E_1(x)$ subroutine. Enter this subroutine, then enter the remaining steps listed here.

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
110	76	2nd Lbl	138	13	C	166	53	(	194	00	0	222	54	)
111	33	x^2	139	42	STO	167	53	(	195	00	00	223	44	SUM
112	42	STO	140	12	12	168	03	3	196	85	+	224	10	10
113	05	05	141	91	R/S	169	09	9	197	02	2	225	43	RCL
114	76	2nd Lbl	142	76	2nd Lbl	170	93	.	198	65	x	226	13	13
115	22	INV	143	14	D	171	05	5	199	43	RCL	227	22	INV
116	43	RCL	144	42	STO	172	01	1	200	21	21	228	44	SUM
117	22	22	145	13	13	173	65	x	201	54	)	229	14	14
118	42	STO	146	91	R/S	174	43	RCL	202	65	x	230	43	RCL
119	14	14	147	76	2nd Lbl	175	17	17	203	43	RCL	231	11	11
120	00	0	148	15	E	176	65	x	204	18	18	232	42	STO
121	42	STO	149	42	STO	177	43	RCL	205	65	x	233	26	26
122	25	25	150	14	14	178	18	18	206	43	RCL	234	43	RCL
123	91	R/S	151	42	STO	179	65	x	207	20	20	235	10	10
124	42	STO	152	22	22	180	43	RCL	208	65	x	236	97	2nd Dsz
125	06	06	153	91	R/S	181	19	19	209	43	RCL	237	06	6
126	91	R/S	154	76	2nd Lbl	182	65	x	210	25	25	238	11	A
127	76	2nd Lbl	155	10	2nd E'	183	43	RCL	211	55	÷	239	00	0
128	11	A	156	53	(	184	12	12	212	43	RCL	240	42	STO
129	42	STO	157	43	RCL	185	33	x^2	213	15	15	241	26	26
130	10	10	158	11	11	186	55	÷	214	55	÷	242	97	2nd Dsz
131	91	R/S	159	75	-	187	43	RCL	215	43	RCL	243	05	5
132	76	2nd Lbl	160	43	RCL	188	15	15	216	16	16	244	22	INV
133	12	B	161	26	26	189	55	÷	217	65	x	245	43	RCL
134	42	STO	162	54	)	190	43	RCL	218	07	7	246	10	10
135	11	11	163	42	STO	191	14	14	219	00	0	247	92	INV SBR
136	91	R/S	164	25	25	192	54	)	220	93	.			
137	76	2nd Lbl	165	53	(	193	71	SBR	221	06	6			

PROGRAM TITLE: Single Vertical Fracture, Wellbore Case

PARTITIONING: Normal

PROGRAM DESCRIPTION: Solves for pressure buildup at the well bore for a well with a single vertical fracture passing centrally through the wellbore (Gringarten, et. al., 1974).

Program calculates:

$$P_{WB} = P_i + P_{WD}\left(\frac{141.2q\mu\beta}{kh}\right)$$

where:

$$P_{WD} = \sqrt{\pi t_D}\ \mathrm{erf}\left(\frac{1}{2\sqrt{t_D}}\right) + \frac{1}{2} E_1\left(\frac{1}{4t_D}\right)$$

and

$$t_D = \frac{6.33\text{x}10^{-3}kt}{\phi\mu c(x_f)^2}$$

NOTE: Programs for exponential integral, $E_1(x)$, error function, erf(x), are documented separately.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Enter initial pressure	P_i (psi)	GTO	x^2	R/S	P_i
2	Enter fracture length	x_f (ft)	A			x_f
3	Enter injection rate	q (STB/D)	B			q
4	Enter injection time	t (D)	C			t
5	Enter permeability	k (md)	STO	1	4	k
6	Enter reservoir thickness	h (ft)	STO	1	5	h
7	Enter porosity	ϕ (fraction)	STO	1	6	ϕ
8	Enter viscosity	μ (cp)	STO	1	7	μ
9	Enter system compressibility	c (1/psi)	STO	1	8	c
10	Enter formation volume factor	β (RB/STB)	STO	1	9	β
11	Start execution of calculation		2nd	E'		P_{WB}

NOTE: For next well or data, enter only data which have changed.

PROGRAM

NOTE: Program steps 000-109 are separately documented as the $E_1(x)$ subroutine and steps 110-219 are documented as the erf(x) subroutine. Enter these two subroutines in order, then enter the remaining steps listed here.

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
220	76	2nd Lbl	247	03	3	274	53	(	301	71	SBR
221	33	x^2	248	03	3	275	24	CE	302	00	0
222	42	STO	249	65	x	276	34	$\sqrt{x}$	303	00	00
223	10	10	250	43	RCL	277	65	x	304	55	÷
224	91	R/S	251	14	14	278	02	2	305	02	2
225	76	2nd Lbl	252	65	x	279	54	)	306	54	)
226	11	A	253	43	RCL	280	35	1/x	307	65	x
227	42	STO	254	13	13	281	71	SBR	308	01	1
228	11	11	255	55	÷	282	01	1	309	04	4
229	91	R/S	256	43	RCL	283	10	10	310	01	1
230	76	2nd Lbl	257	16	16	284	65	x	311	93	.
231	12	B	258	55	÷	285	53	(	312	02	2
232	42	STO	259	43	RCL	286	89	2nd π	313	65	x
233	12	12	260	17	17	287	65	x	314	43	RCL
234	91	R/S	261	55	÷	288	43	RCL	315	12	12
235	76	2nd Lbl	262	43	RCL	289	20	20	316	65	x
236	13	C	263	18	18	290	54	)	317	43	RCL
237	42	STO	264	55	÷	291	34	$\sqrt{x}$	318	17	17
238	13	13	265	43	RCL	292	54	)	319	65	x
239	91	R/S	266	11	11	293	85	+	320	43	RCL
240	76	2nd Lbl	267	33	x^2	294	53	(	321	19	19
241	10	2nd E'	268	54	)	295	43	RCL	322	55	÷
242	53	(	269	42	STO	296	20	20	323	43	RCL
243	93	.	270	20	20	297	65	x	324	14	14
244	00	0	271	53	(	298	04	4	325	55	÷
245	00	0	272	53	(	299	54	)	326	43	RCL
246	06	6	273	53	(	300	35	1/x	327	15	15

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
328	85	+									
329	43	RCL									
330	10	10									
331	54	)									
332	92	INV SBR									

PROGRAM TITLE: Single Vertical Fracture, General Case.

PARTITIONING: Normal

PROGRAM DESCRIPTION: Solves for pressure buildup (decline) of any point in an infinite confined reservoir as a result of injection (pumping) at a constant rate into (from) a well with a single vertical fracture passing centrally through the wellbore (Gringarten, et al, 1974).

Program Calculates:

$$P_{xy} = P_i + P_D \left(\frac{141.2 q\mu\beta}{kh}\right)$$

where:

$$P_D = \frac{1}{2}(\ln t_D + 2.809) + \sigma(x_D, y_D, r_D)$$

and

$$t_D = \frac{6.33 \times 10^{-3} kt}{\phi\mu c (x_f)^2}$$

At $2y_D \tan^{-1}(2y_D/r_D^2-1) \geq 0$

$$\sigma = \frac{1}{4}\left[(x_D-1)\ln\left(y_D^2 + (x_D-1)^2\right) - (x_D+1)\ln\left(y_D^2+(x_D+1)^2\right) - 2y_D \tan^{-1}\left(\frac{2y_D}{r_D^2-1}\right)\right]$$

At $2y_D \tan^{-1}(2y_D/r_D^2-1) < 0$

$$\sigma = \frac{1}{4}\left[(x_D-1)\ln\left(y_D^2+(x_D-1)^2\right) - (x_D+1)\ln\left(y_D^2+(x_D+1)^2\right)\right]$$

NOTE: The solution given applies within ± 1 percent, when $t_D > 12.5\ (r_D^2 + \frac{1}{3})$.

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Enter initial pressure	P_i(psi)	GTO	x^2	R/S	P_i
2	Enter fracture length	x_f(ft)	A			x_f
3	Enter distance to point of interest in x direction	x(ft)	B			x_D
4	Enter distance to point of interest in y direction	y(ft)	C			y_D
5	Enter injection or pumping rate	q(STB/D)	D			q
6	Enter time since injection into or pumping from well began	t(D)	E			t
7	Enter average horizontal reservoir permeability	k(md)	STO	1	6	k
8	Enter reservoir thickness	h(ft)	STO	1	7	h
9	Enter reservoir porosity	ϕ(fraction)	STO	1	8	ϕ
10	Enter viscosity	μ(cp)	STO	1	9	μ
11	Enter system compressibility	c(1/psi)	STO	2	0	c
12	Enter formation volume factor	β(RB/STB)				β
13	Start execution of calculation		2nd	E'		P_{xy}
	NOTE: For next well or data set, enter only data which have changed.					

PROGRAM

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
000	76	2nd Lbl	030	13	13	060	65	x	090	43	RCL
001	33	x^2	031	91	R/S	061	43	RCL	091	12	12
002	42	STO	032	76	2nd Lbl	062	15	15	092	75	-
003	10	10	033	14	D	063	55	÷	093	01	1
004	91	R/S	034	42	STO	064	43	RCL	094	54	)
005	76	2nd Lbl	035	14	14	065	18	18	095	33	x^2
006	11	A	036	91	R/S	066	55	÷	096	85	+
007	42	STO	037	76	2nd Lbl	067	43	RCL	097	43	RCL
008	11	11	038	15	E	068	19	19	098	13	13
009	91	R/S	039	42	STO	069	55	÷	099	33	x^2
010	76	2nd Lbl	040	15	15	070	43	RCL	100	54	)
011	12	B	041	91	R/S	071	20	20	101	23	ln x
012	53	(	042	76	2nd Lbl	072	55	÷	102	65	x
013	24	CE	043	10	2nd E'	073	43	RCL	103	53	(
014	55	÷	044	70	2nd Rad	074	11	11	104	43	RCL
015	43	RCL	045	00	0	075	33	x^2	105	12	12
016	11	11	046	32	x⇄t	076	54	)	106	75	-
017	54	)	047	53	(	077	23	ln x	107	01	1
018	42	STO	048	53	(	078	85	+	108	54	)
019	12	12	049	53	(	079	02	2	109	75	-
020	91	R/S	050	53	(	080	93	.	110	53	(
021	76	2nd Lbl	051	93	.	081	08	8	111	53	(
022	13	C	052	00	0	082	01	1	112	43	RCL
023	53	(	053	00	0	083	54	)	113	12	12
024	24	CE	054	06	6	084	55	÷	114	85	+
025	55	÷	055	03	3	085	02	2	115	01	1
026	43	RCL	056	03	3	086	85	+	116	54	)
027	11	11	057	65	x	087	53	(	117	33	x^2
028	54	)	058	43	RCL	088	53	(	118	85	+
029	42	STO	059	16	16	089	53	(	119	43	RCL

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
120	13	13	152	30	2nd tan	182	21	21			
121	33	x^2	153	65	x	183	55	÷			
122	54	)	154	02	2	184	43	RCL			
123	23	ln x	155	65	x	185	16	16			
124	65	x	156	43	RCL	186	55	÷			
125	53	(	157	13	13	187	43	RCL			
126	43	RCL	158	54	)	188	17	17			
127	12	12	159	77	2nd x≥t	189	85	+			
128	85	+				190	43	RCL			
129	01	1				191	10	10			
130	54	)	160	44	SUM	192	54	)			
131	75	−	161	00	0	193	92	INV SBR			
132	53	(	162	76	2nd Lbl						
133	53	(	163	44	SUM						
134	02	2	164	54	)						
135	65	x	165	55	÷						
136	43	RCL	166	04	4						
137	13	13	167	54	)						
138	55	÷	168	65	x						
139	53	(	169	01	1						
140	43	RCL	170	04	4						
141	12	12	171	01	1						
142	33	x^2	172	93	.						
143	85	+	173	02	2						
144	43	RCL	174	65	x						
145	13	13	175	43	RCL						
146	33	x^2	176	14	14						
147	75	−	177	65	x						
148	01	1	178	43	RCL						
149	54	)	179	19	19						
150	54	)	180	65	x						
151	22	INV	181	43	RCL						

PROGRAM TITLE: Single Horizontal Fracture

PARTITIONING: Normal

PROGRAM DESCRIPTION: Calculates the pressure buildup at any location for a well intersected by a single horizontal fracture (Gringarten, and Ramey, 1974).

Program calculates:

$$P_{r,z} = P_i + \frac{141.2q\mu\beta}{kh} P_D(r_D, z_D, t_D)$$

where:

$$P_D(r_D, z_D, t_D) = P_D(r_D, t_D) + \sigma(r_D, z_D, t_D)$$

and

$$t_D = \frac{6.33\times10^{-3}k_r t}{\phi\mu c r_f^2}$$

At $t_D \geq 12.5(2r_D^2+1)$ and $t_D \geq 5 \frac{h_D^2}{\pi^2}$:

$$P_D = \frac{1}{2}[\ln t_D + 1.81 - r_D^2] \text{ for } 0 \leq r_D \leq 1$$

and

$$P_D = \frac{1}{2}[\ln(t_D/r_D^2) + 0.81] \text{ for } r_D > 1$$

When:

$$r > r_i = r_f \frac{10h}{\pi} \sqrt{k_r/k_z}, \ \sigma = 0$$

For $r = 0$ (at wellbore)

$$\sigma = \frac{2}{3} h_D^2 \left(1-3\frac{z_f}{h} \left(1-\frac{z_f}{h}\right)\right) -\frac{4}{\pi} h_D \sum_{n=1}^{\infty} \frac{1}{n} \cos^2 (n\pi) \left(\frac{z_f}{h}\right) \left(K_1 \left(\frac{n\pi}{h_D}\right)\right)\Bigg)$$

where:

$$K_1(x) \cong \frac{1}{x} \text{ for } x < 5$$

and

$$K_1(x) \cong \frac{\pi}{2x}\left(1+\frac{3}{8x}\right)e^{-x} \text{ for } x \geq 5$$

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	enter initial pressure	P_i(psi)	GTO	Inv	R/S	P_i
2	enter injection rate	q_f(STB/D)	A			q_f
3	enter distance from well	r(ft)	B			r
4	enter injection time	t(D)	C			t
5	enter radial length of fracture	r_f(ft)	D			r_f
6	enter radial permeability	$k=k_r$(md)	STO	1	5	k_r
7	enter vertical permeability	k_z(md)	STO	1	6	k_z
8	enter reservoir thickness	h(ft)	STO	1	7	h
9	enter distance from bottom of reservoir to center of fracture	z_f(ft)	STO	1	8	z_f
10	enter porosity	ϕ(fraction)	STO	1	9	ϕ
11	enter viscosity	μ(cp)	STO	2	0	μ
12	enter total system compressibility	c(1/psi)	STO	2	1	c
13	enter formation volume factor	β(RB/STB)	STO	2	2	β
14	start execution of calculation		E			$P_{r,z}$ or 0
	NOTE: For next calculation re-enter only data which has changed. z_f is needed at r = 0 only. Final display of a flash followed by 0 indicates violation of some condition. If x ⇄ t causes same display as Rcl 00 increase r. If x ⇄ t does not cause same display as Rcl 00 increase t.					

PROGRAM

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
000	76	2nd Lbl	030	00	0	060	05	5	090	43	RCL
001	22	INV	031	06	6	061	65	x	091	17	17
002	42	STO	032	03	3	062	53	(	092	33	x^2
003	10	10	033	03	3	063	53	(	093	55	÷
004	91	R/S	034	65	X	064	43	RCL	094	43	RCL
005	76	2nd Lbl	035	43	RCL	065	12	12	095	14	14
006	11	A	036	15	15	066	55	÷	096	33	x^2
007	42	STO	037	65	X	067	43	RCL	097	65	x
008	11	11	038	43	RCL	068	14	14	098	43	RCL
009	91	R/S	039	13	13	069	54	)	099	15	15
010	76	2nd Lbl	040	55	÷	070	42	STO	100	55	÷
011	12	B	041	43	RCL	071	24	24	101	43	RCL
012	42	STO	042	19	19	072	33	x^2	102	16	16
013	12	12	043	55	÷	073	65	x	103	54	)
014	91	R/S	044	43	RCL	074	02	2	104	42	STO
015	76	2nd Lbl	045	20	20	075	85	+	105	23	23
016	13	C	046	55	÷	076	01	1	106	55	÷
017	42	STO	047	43	RCL	077	54	)	107	89	2nd π
018	13	13	048	21	21	078	54	)	108	33	x^2
019	91	R/S	049	55	÷	079	32	x⇄t	109	54	)
020	76	2nd Lbl	050	43	RCL	080	43	RCL	110	32	x⇄t
021	14	D	051	14	14	081	26	26	111	43	RCL
022	42	STO	052	33	x^2	082	22	INV	112	26	26
023	14	14	053	54	)	083	77	2nd x≥t	113	22	INV
024	91	R/S	054	42	STO	084	02	2	114	77	2nd x≥t
025	76	2nd Lbl	055	26	26	085	22	22	115	02	2
026	15	E	056	53	(	086	53	(	116	22	22
027	53	(	057	01	1	087	05	5	117	00	0
028	93	.	058	02	2	088	65	x	118	32	x⇄t
029	00	0	059	93	.	089	53	(	119	43	RCL

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
120	12	12	150	22	INV	180	53	(	210	43	RCL
121	67	2nd x=t	151	77	2nd $x \geq t$	181	53	(	211	20	20
122	02	2	152	02	2	182	43	RCL	212	65	x
123	27	27	153	22	22	183	26	26	213	43	RCL
124	53	(	154	01	1	184	55	÷	214	22	22
125	43	RCL	155	32	$x \rightleftarrows t$	185	43	RCL	215	85	+
126	14	14	156	43	RCL	186	24	24	216	43	RCL
127	85	+	157	24	24	187	33	x^2	217	10	10
128	01	1	158	77	2nd $x \geq t$	188	54	)	218	54	)
129	00	0	159	01	1	189	23	ln x	219	61	GTO
130	65	x	160	79	79	190	85	+	220	02	2
131	43	RCL	161	53	(	191	93	.	221	26	26
132	17	17	162	53	(	192	08	8	222	00	0
133	55	÷	163	43	RCL	193	01	1	223	35	1/x
134	89	2nd π	164	26	26	194	54	)	224	66	2nd Pause
135	65	x	165	23	ln x	195	65	x	225	25	CLR
136	53	(	166	85	+	196	07	7	226	92	INV SBR
137	43	RCL	167	01	1	197	00	0	227	70	2nd Rad
138	15	15	168	93	.	198	93	.	228	53	(
139	55	÷	169	08	8	199	06	6	229	02	2
140	43	RCL	170	01	1	200	55	÷	230	55	÷
141	16	16	171	75	-	201	43	RCL	231	03	3
142	54	)	172	43	RCL	202	15	15	232	65	x
143	34	$\sqrt{x}$	173	24	24	203	55	÷	233	43	RCL
144	54	)	174	33	x^2	204	43	RCL	234	23	23
145	42	STO	175	54	)	205	17	17	235	65	x
146	00	00	176	61	GTO	206	65	x	236	53	(
147	32	$x \rightleftarrows t$	177	01	1	207	43	RCL	237	01	1
148	43	RCL	178	95	95	208	11	11	238	75	-
149	12	12	179	53	(	209	65	x	239	03	3

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
240	65	×	270	00	00	300	42	STO	330	55	÷
241	53	(	271	54	)	301	31	31	331	43	RCL
242	43	RCL	272	42	STO	302	05	5	332	31	31
243	18	18	273	32	32	303	32	x⇄t	333	54	)
244	55	÷	274	53	(	304	43	RCL	334	65	×
245	43	RCL	275	53	(	305	31	31	335	43	RCL
246	17	17	276	24	CE	306	77	2nd x≥t	336	31	31
247	54	)	277	65	×	307	03	3	337	94	+/-
248	42	STO	278	89	2nd π	308	13	13	338	22	INV
249	25	25	279	54	)	309	35	1/x	339	23	ln x
250	65	×	280	39	2nd cos	310	61	GTO	340	54	)
251	53	(	281	33	x^2	311	03	3	341	54	)
252	01	1	282	55	÷	312	41	41	342	65	×
253	75	-	283	43	RCL	313	53	(	343	04	4
254	43	RCL	284	32	32	314	53	(	344	55	÷
255	25	25	285	65	×	315	89	2nd π	345	89	2nd π
256	54	)	286	43	RCL	316	55	÷	346	65	×
257	54	)	287	25	25	317	02	2	347	43	RCL
258	54	)	288	65	×	318	65	×	348	23	23
259	42	STO	289	53	(	319	43	RCL	349	34	$\sqrt{x}$
260	29	29	290	53	(	320	31	31	350	54	)
261	05	5	291	43	RCL	321	54	)	351	94	+/-
262	00	0	292	32	32	322	34	$\sqrt{x}$	352	53	(
263	42	STO	293	65	×	323	65	×	353	24	CE
264	00	00	294	89	2nd π	324	53	(	354	85	+
265	53	(	295	55	÷	325	01	1	355	43	RCL
266	05	5	296	43	RCL	326	85	+	356	29	29
267	01	1	297	23	23	327	03	3	357	54	)
268	75	-	298	34	$\sqrt{x}$	328	55	÷	358	48	2nd Exc
269	43	RCL	299	54	)	329	08	8	359	29	29

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
360	32	x⇄t	390	93	.						
361	93	.	391	08	8						
362	00	0	392	01	1						
363	00	0	393	85	+						
364	01	1	394	43	RCL						
365	32	x⇄t	395	26	26						
366	53	(	396	23	ln x						
367	24	CE	397	54	)						
368	55	÷	398	53	(						
369	43	RCL	399	24	CE						
370	29	29	400	61	GTO						
371	75	-	401	01	1						
372	01	1	402	95	95						
373	54	)									
374	50	2nd |x|									
375	22	INV									
376	77	2nd x≥t									
377	03	3									
378	83	83									
379	97	2nd Dsz									
380	00	0									
381	02	2									
382	65	65									
383	53	(									
384	43	RCL									
385	29	29									
386	65	×									
387	02	2									
388	85	+									
389	01	1									

PROGRAM TITLE: Partially Penetrating Wells

PARTITIONING: Normal

PROGRAM DESCRIPTION: Solves for pressure buildup at any location in an infinite confined reservoir as a result of injection at a constant rate into a well that partially penetrates the reservoir or a well that fully penetrates the reservoir and is only perforated or screened through part of the reservoir (Hantush, 1961)

Program Calculates:

$$P_r = P_i + P_D \left(\frac{141.2\ q\mu\beta}{kh}\right)$$

where:

$$P_D = \frac{1}{2} \left[E_1(1/4t_D) + f\ (z,l,r,h)\right]$$

and

$$t_D = \frac{6.33\text{x}10^{-3}kt}{\phi\mu c r^2}$$

For $\dfrac{h^2}{2t_D r^2} < 1$

$$f = \frac{4h}{\pi(l-d)} \sum_{n=1}^{\infty} \frac{1}{n} K_0 \left(\frac{n\pi r}{h}\right)\left(\sin \frac{\pi n l}{h} - \sin \frac{\pi n d}{h}\right) \cos \frac{n\pi z}{h}$$

where $K_0(x) \simeq \ln \dfrac{1.12}{x}$ for $x < 0.5$

$$K_0(x) \simeq \sqrt{\frac{\pi}{2x}} \left(1 - \frac{1}{8x}\right) e^{-x} \quad \text{for } x \geq 0.5$$

Note: Program for exponential integral, $E_1(x)$, is documented separately. $K_0(x)$ is the modified zero order Bessel function of second kind.

USER INSTRUCTIONS

STEP		ENTER	PRESS			DISPLAY
1	enter injection (pumping) rate	q(STB/D)	A			q
2	enter time since injection into or pumping from well began	t(D)	B			t
3	enter radial distance from well to point of investigation	r(ft)	C			r
4	enter vertical distance from top of reservoir to point at which buildup pressure is to be calculated	z(ft)	D			z
5	enter reservoir thickness	h(ft)	STO	1	4	h
6	enter length of penetration of well	l(ft)	STO	1	5	l
7	enter depth to top of perforations or screen	d(ft)	STO	1	6	d
8	enter average horizontal reservoir permeability	k(md')	STO	1	7	k
9	enter initial reservoir pressure	P_i(psi)	STO	1	8	P_i
10	enter reservoir porosity	ϕ(fraction)	STO	1	9	ϕ
11	enter viscosity	μ(cp)	STO	2	0	μ
12	enter system compressibility	c(1/psi)	STO	2	1	c
13	enter formation volume factor	β(RB/STB)	STO	2	2	β
14	start execution of calculation		E			P_r
	NOTE: For subsequent calculations re-enter only data that have changed, then press E.					

PROGRAM

NOTE: Program steps 000-109 are separately documented as the $E_1(x)$ subroutine. Enter this subroutine, then enter the remaining steps listed here.

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
110	76	2nd Lbl	138	05	5	166	42	STO	194	42	STO
111	11	A	139	01	1	167	33	33	195	00	00
112	42	STO	140	65	x	168	53	(	196	00	0
113	10	10	141	43	RCL	169	43	RCL	197	42	STO
114	91	R/S	142	19	19	170	24	24	198	04	04
115	76	2nd Lbl	143	65	x	171	65	x	199	42	STO
116	12	B	144	43	RCL	172	43	RCL	200	06	06
117	42	STO	145	20	20	173	14	14	201	53	(
118	11	11	146	65	x	174	33	x^2	202	53	(
119	91	R/S	147	43	RCL	175	55	÷	203	09	9
120	76	2nd Lbl	148	21	21	176	43	RCL	204	09	9
121	13	C	149	65	x	177	12	12	205	75	-
122	42	STO	150	43	RCL	178	33	x^2	206	43	RCL
123	12	12	151	12	12	179	65	x	207	00	00
124	91	R/S	152	33	x^2	180	02	2	208	54	)
125	76	2nd Lbl	153	55	÷	181	54	)	209	42	STO
126	14	D	154	43	RCL	182	32	x⇄t	210	01	01
127	42	STO	155	17	17	183	01	1	211	65	x
128	13	13	156	55	÷	184	77	2nd x≥t	212	89	2nd π
129	91	R/S	157	43	RCL	185	01	1	213	55	÷
130	76	2nd Lbl	158	11	11	186	92	92	214	43	RCL
131	15	E	159	54	)	187	00	0	215	14	14
132	70	2nd Rad	160	42	STO	188	35	1/x	216	54	)
133	53	(	161	24	24	189	66	2nd Pause	217	42	STO
134	53	(	162	65	x	190	24	CE	218	02	02
135	03	3	163	04	4	191	92	INV SBR	219	93	.
136	09	9	164	54	)	192	09	9	220	05	5
137	93	.	165	35	1/x	193	08	8	221	32	x⇄t

LOC	CODE	KEY
222	53	(
223	53	(
224	43	RCL
225	01	01
226	35	1/x
227	65	x
228	53	(
229	43	RCL
230	02	02
231	65	x
232	43	RCL
233	12	12
234	54	)
235	42	STO
236	03	03
237	22	INV
238	77	2nd x≥t
239	02	2
240	73	73
241	53	(
242	53	(
243	89	2nd π
244	55	÷
245	02	2
246	55	÷
247	43	RCL
248	03	03
249	54	)
250	34	√x
251	65	x
252	53	(
253	01	1
254	75	-
255	53	(
256	08	8
257	65	x
258	43	RCL
259	03	03
260	54	)
261	35	1/x
262	54	)
263	65	x
264	43	RCL
265	03	03
266	94	+/-
267	22	INV
268	23	ln x
269	54	)
270	61	GTO
271	02	2
272	83	83
273	53	(
274	01	1
275	93	.
276	01	1
277	02	2
278	55	÷
279	43	RCL
280	03	03
281	54	)
282	23	ln x
283	32	x⇄t
284	93	.
285	00	0
286	00	0
287	01	1
288	32	x⇄t
289	42	STO
290	05	05
291	53	(
292	24	CE
293	85	+
294	43	RCL
295	06	06
296	54	)
297	48	2nd Exc
298	06	06
299	53	(
300	24	CE
301	55	÷
302	43	RCL
303	06	06
304	75	-
305	01	1
306	54	)
307	50	2nd |x|
308	77	2nd x≥t
309	03	3
310	14	14
311	00	0
312	42	STO
313	00	00
314	43	RCL
315	05	05
316	65	x
317	53	(
318	53	(
319	43	RCL
320	02	02
321	65	x
322	43	RCL
323	15	15
324	54	)
325	38	2nd sin
326	75	-
327	53	(
328	43	RCL
329	02	02
330	65	x
331	43	RCL
332	16	16
333	54	)
334	38	2nd sin
335	54	)
336	65	x
337	53	(
338	43	RCL
339	02	02
340	65	x
341	43	RCL
342	13	13
343	54	)
344	39	2nd cos
345	54	)
346	54	)
347	44	SUM
348	04	04
349	97	2nd Dsz
350	00	0
351	02	2
352	01	01
353	53	(
354	43	RCL
355	04	04
356	65	x
357	04	4

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
358	65	x	391	65	x						
359	43	RCL	392	43	RCL						
360	14	14	393	22	22						
361	55	÷	394	55	÷						
362	89	2nd π	395	43	RCL						
363	55	÷	396	17	17						
364	53	(	397	55	÷						
365	43	RCL	398	43	RCL						
366	15	15	399	14	14						
367	75	−	400	65	x						
368	43	RCL	401	01	1						
369	16	16	402	04	4						
370	54	)	403	01	1						
371	54	)	404	54	)						
372	53	(	405	85	+						
373	53	(	406	43	RCL						
374	53	(	407	18	18						
375	24	CE	408	54	)						
376	85	+	409	92	INV SBR						
377	43	RCL									
378	24	24									
379	71	SBR									
380	00	0									
381	00	00									
382	54	)									
383	55	÷									
384	02	2									
385	65	x									
386	43	RCL									
387	10	10									
388	65	x									
389	43	RCL									
390	20	20									

PROGRAM TITLE: Semiconfined Reservoirs

PARTITIONING: 4 2nd Op 17

PROGRAM DESCRIPTION: Solves for pressure buildup (decline) at any point in an infinite reservoir with a leaky confining bed or beds as a result of injection (pumping) at a constant rate into (from) a single fully penetrating well (Hantush and Jacob, 1955).

Program Calculates:

$$P_r = P_i + P_{DL}\left(\frac{141.2q\mu\beta}{kh}\right)$$

where:

$$P_{DL} = \frac{1}{2}\left(I_0(r/B)E_1(u) - e^{-u}\left[0.5772 + \ln\left(\frac{r^2}{4B^2u}\right) + E_1\left(\frac{r^2}{4B^2u}\right) - \left(\frac{r^2}{4B^2u}\right) + \right.\right.$$
$$\left.\left. + \left(\frac{I_0(r/B)-1}{u}\right)\right] + e^{-1/u}\sum_{n=1}^{6}\sum_{m=1}^{n}\frac{(-1)^{n+m}(n-m+1)!}{(n+2)!^2\,u^{n-m}}\left(\frac{r^2}{4B^2}\right)^n\right) \quad \text{for } u > 1.0$$

or

$$P_{DL} = -\frac{1}{2}\left(I_0(r/B)E_1\left(\frac{r^2}{4B^2u}\right) - e^{(r^2/4B^2u)}\left[0.5772 + \ln(u) + E_1(u) - \right.\right.$$
$$\left.\left. - u + \frac{I_0(r/B)-1}{r^2/4B^2u}\right] + u^2\sum_{n=1}^{6}\sum_{m=1}^{n}\frac{(-1)^{n+m}(n-m+1)!}{(n+2)!^2\,u^{m-n}}\left(\frac{r^2}{4B^2}\right)^m\right) + K_0(r/B)$$

for $u \leq 1.0$

and:

$B = \sqrt{\frac{khh_c}{k_c}}$ for leakage in one direction, or $B = \sqrt{\frac{khh_c h'_c}{k'_c h_c + k_c h'_c}}$ for leakage in two directions.

$$u = \frac{1}{4t_D} = \frac{39.5\phi\mu c r^2}{kt}$$

$I_0(x)$ = zero order modified Bessel function of the first kind

$$I_0(x) \cong 1 + \sum_{i=1}^{6} \frac{(x^2/4)^i}{(i!)^2}$$

$K_o(x)$ = zero order modified Bessel function of the second kind

$$K_o(x) \cong \frac{x^2}{4} + 0.02344x^4 - I_0(x)\left[0.5772 + \ln\left(\frac{x}{2}\right)\right]$$

USER INSTRUCTIONS

STEP	PROCEDURE	ENTER	PRESS			DISPLAY
1	Enter injection or pumping rate	q(STB/D)	A			
2	Enter radial distance from well to point of investigation	r(ft)	B			r
3	Enter time since injection into or pumping from well began	t(D)	C			t
4	Enter initial reservoir pressure	P_i(psi)	D			P_i
5	Enter average horizontal reservoir permeability	k(md)	STO	1	4	k
6	Enter average vertical permeability of leaky confining bed (see note below)	k_c(md)	STO	1	5	k_c
7	Enter reservoir thickness	h(ft)	STO	1	6	h
8	Enter confining bed thickness (see note below)	h_c(ft)	STO	1	7	h_c
9	Enter reservoir porosity	ϕ(fract)	STO	1	8	ϕ
10	Enter viscosity	μ(cp)	STO	1	9	μ
11	Enter system compressibility	c(1/psi)	STO	2	0	c
12	Enter formation volume factor	β(RB/STB)	STO	2	1	β
13	Start execution of calculation		E			P_r
	NOTE: For leakage in two directions enter $(h_c \times h_c')$ for h_c and $(k_c' h_c + k_c h_c')$ for k_c.					

PROGRAM

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
000	42	STO	034	42	STO	068	65	x	102	06	6
001	30	30	035	38	38	069	43	RCL	103	02	2
002	32	x⇄t	036	06	6	070	32	32	104	15	15
003	01	1	037	42	STO	071	54	)	105	53	(
004	00	0	038	03	03	072	42	STO	106	53	(
005	32	x⇄t	039	93	.	073	32	32	107	43	RCL
006	22	INV	040	00	0	074	54	)	108	31	31
007	77	2nd x≥t	041	00	0	075	87	2nd Ifflg	109	85	+
008	00	0	042	01	1	076	05	5	110	02	2
009	12	12	043	32	x⇄t	077	00	0	111	54	)
010	00	0	044	86	2nd Stflg	078	87	87	112	65	x
011	92	INV SBR	045	05	5	079	86	2nd Stflg	113	43	RCL
012	53	(	046	53	(	080	05	5	114	38	38
013	23	ln x	047	03	3	081	22	INV	115	54	)
014	85	+	048	06	6	082	86	2nd Stflg	116	42	STO
015	93	.	049	75	−	083	04	4	117	38	38
016	05	5	050	43	RCL	084	61	GTO	118	43	RCL
017	07	7	051	00	00	085	00	0	119	31	31
018	07	7	052	54	)	086	93	93	120	42	STO
019	02	2	053	42	STO	087	22	INV	121	01	01
020	54	)	054	31	31	088	86	2nd Stflg	122	42	STO
021	42	STO	055	53	(	089	05	5	123	37	37
022	33	33	056	43	RCL	090	86	2nd Stflg	124	43	RCL
023	03	3	057	30	30	091	04	4	125	32	32
024	05	5	058	45	y^x	092	94	+/-	126	42	STO
025	42	STO	059	43	RCL	093	53	(	127	36	36
026	00	00	060	31	31	094	24	CE	128	53	(
027	00	0	061	55	÷	095	85	+	129	43	RCL
028	42	STO	062	43	RCL	096	43	RCL	130	31	31
029	34	34	063	31	31	097	33	33	131	75	−
030	01	1	064	55	÷	098	54	)	132	43	RCL
031	42	STO	065	53	(	099	42	STO	133	01	01
032	32	32	066	43	RCL	100	39	39	134	85	+
033	02	2	067	31	31	101	87	2nd Ifflg	135	01	1

LOC	CODE	KEY
136	54	)
137	42	STO
138	35	35
139	53	(
140	53	(
141	43	RCL
142	27	27
143	65	x
144	43	RCL
145	26	26
146	54	)
147	45	y^x
148	43	RCL
149	31	31
150	87	2nd Ifflg
151	01	1
152	01	1
153	56	56
154	43	RCL
155	35	35
156	65	x
157	43	RCL
158	36	36
159	55	÷
160	43	RCL
161	26	26
162	45	y^x
163	53	(
164	43	RCL
165	01	01
166	75	-
167	01	1
168	54	)
169	87	2nd Ifflg
170	01	1
171	01	1
172	74	74
173	94	+/-
174	55	÷
175	43	RCL
176	38	38
177	33	x^2
178	54	)
179	87	2nd Ifflg
180	04	4
181	01	1
182	89	89
183	86	2nd Stflg
184	04	4
185	22	INV
186	61	GTO
187	01	1
188	92	92
189	22	INV
190	86	2nd Stflg
191	04	4
192	44	SUM
193	34	34
194	53	(
195	43	RCL
196	36	36
197	55	÷
198	43	RCL
199	37	37
200	54	)
201	42	STO
202	36	36
203	53	(
204	43	RCL
205	37	37
206	75	-
207	01	1
208	54	)
209	42	STO
210	37	37
211	97	2nd Dsz
212	01	1
213	01	1
214	28	28
215	43	RCL
216	39	39
217	48	2nd Exc
218	33	33
219	97	2nd Dsz
220	03	3
221	02	2
222	43	43
223	86	2nd Stflg
224	06	6
225	22	INV
226	87	2nd Ifflg
227	05	5
228	02	2
229	43	43
230	53	(
231	24	CE
232	55	÷
233	43	RCL
234	33	33
235	75	-
236	01	1
237	54	)
238	50	2nd $\lvert x \rvert$
239	22	INV
240	77	2nd x≥t
241	02	2
242	47	47
243	97	2nd Dsz
244	00	0
245	00	0
246	46	46
247	43	RCL
248	33	33
249	94	+/-
250	92	INV SBR
251	76	2nd Lbl
252	11	A
253	42	STO
254	10	10
255	91	R/S
256	76	2nd Lbl
257	12	B
258	42	STO
259	11	11
260	91	R/S
261	76	2nd Lbl
262	13	C
263	42	STO
264	12	12
265	91	R/S
266	76	2nd Lbl
267	14	D
268	42	STO
269	13	13
270	91	R/S
271	76	2nd Lbl
272	15	E
273	22	INV
274	86	2nd Stflg
275	01	1

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
276	22	INV	311	86	2nd Stflg	346	32	32	381	43	RCL
277	86	2nd Stflg	312	02	2	347	54	)	382	20	20
278	02	2	313	06	6	348	42	STO	383	65	x
279	22	INV	314	42	STO	349	32	32	384	43	RCL
280	86	2nd Stflg	315	02	02	350	33	x^2	385	11	11
281	03	3	316	01	1	351	54	)	386	33	x^2
282	53	(	317	42	STO	352	44	SUM	387	54	)
283	43	RCL	318	32	32	353	33	33	388	42	STO
284	11	11	319	42	STO	354	97	2nd Dsz	389	26	26
285	33	x^2	320	33	33	355	02	2	390	42	STO
286	55	÷	321	53	(	356	03	3	391	23	23
287	43	RCL	322	07	7	357	21	21	392	32	$x \rightleftarrows t$
288	14	14	323	75	-	358	43	RCL	393	01	1
289	55	÷	324	43	RCL	359	33	33	394	32	$x \rightleftarrows t$
290	43	RCL	325	02	02	360	42	STO	395	22	INV
291	16	16	326	54	)	361	28	28	396	77	2nd $x \geq t$
292	55	÷	327	42	STO	362	53	(	397	04	4
293	43	RCL	328	31	31	363	03	3	398	01	01
294	17	17	329	53	(	364	09	9	399	86	2nd Stflg
295	65	x	330	53	(	365	93	.	400	01	1
296	43	RCL	331	43	RCL	366	05	5	401	53	(
297	15	15	332	30	30	367	01	1	402	43	RCL
298	54	)	333	33	x^2	368	55	÷	403	25	25
299	34	$\sqrt{x}$	334	55	÷	369	43	RCL	404	33	x^2
300	42	STO	335	04	4	370	14	14	405	55	÷
301	25	25	336	54	)	371	55	÷	406	04	4
302	42	STO	337	45	y^x	372	43	RCL	407	55	÷
303	30	30	338	43	RCL	373	12	12	408	43	RCL
304	32	$x \rightleftarrows t$	339	31	31	374	65	x	409	26	26
305	00	0	340	55	÷	375	43	RCL	410	54	)
306	32	$x \rightleftarrows t$	341	53	(	376	18	18	411	42	STO
307	22	INV	342	43	RCL	377	65	x	412	27	27
308	67	2nd x=t	343	31	31	378	43	RCL	413	42	STO
309	03	3	344	65	x	379	19	19	414	22	22
310	13	13	345	43	RCL	380	65	x	415	87	2nd Ifflg

LOC	CODE	KEY
416	01	1
417	04	4
418	37	37
419	22	INV
420	87	2nd Ifflg
421	02	2
422	04	4
423	29	29
424	22	INV
425	86	2nd Stflg
426	02	2
427	86	2nd Stflg
428	03	3
429	43	RCL
430	26	26
431	42	STO
432	22	22
433	43	RCL
434	27	27
435	42	STO
436	23	23
437	53	(
438	53	(
439	87	2nd Ifflg
440	03	3
441	04	4
442	72	72
443	43	RCL
444	28	28
445	65	x
446	43	RCL
447	23	23
448	86	2nd Stflg
449	06	6
450	71	SBR
451	00	0
452	00	00
453	22	INV
454	86	2nd Stflg
455	06	6
456	87	2nd Ifflg
457	02	2
458	05	5
459	19	19
460	85	+
461	53	(
462	93	.
463	05	5
464	07	7
465	07	7
466	02	2
467	85	+
468	43	RCL
469	22	22
470	23	ln x
471	85	+
472	43	RCL
473	22	22
474	71	SBR
475	00	0
476	00	00
477	87	2nd Ifflg
478	03	3
479	05	5
480	25	25
481	75	-
482	43	RCL
483	22	22
484	85	+
485	53	(
486	43	RCL
487	28	28
488	75	-
489	01	1
490	54	)
491	55	÷
492	43	RCL
493	23	23
494	54	)
495	65	x
496	43	RCL
497	23	23
498	94	+/-
499	22	INV
500	23	ln x
501	94	+/-
502	85	+
503	43	RCL
504	34	34
505	65	x
506	43	RCL
507	26	26
508	33	x^2
509	22	INV
510	87	2nd Ifflg
511	01	1
512	05	5
513	19	19
514	34	$\sqrt{x}$
515	94	+/-
516	35	1/x
517	22	INV
518	23	ln x
519	54	)
520	87	2nd Ifflg
521	01	1
522	05	5
523	25	25
524	94	+/-
525	55	÷
526	02	2
527	54	)
528	42	STO
529	34	34
530	87	2nd Ifflg
531	03	3
532	05	5
533	79	79
534	87	2nd Ifflg
535	01	1
536	05	5
537	79	79
538	53	(
539	43	RCL
540	25	25
541	33	x^2
542	55	÷
543	04	4
544	85	+
545	43	RCL
546	25	25
547	45	y^x

LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY	LOC	CODE	KEY
548	04	4	580	43	RCL						
549	65	x	581	34	34						
550	93	.	582	65	x						
551	00	0	583	43	RCL						
552	02	2	584	10	10						
553	03	3	585	65	x						
554	04	4	586	43	RCL						
555	04	4	587	19	19						
556	75	-	588	65	x						
557	43	RCL	589	43	RCL						
558	28	28	590	21	21						
559	65	x	591	65	x						
560	53	(	592	01	1						
561	93	.	593	04	4						
562	05	5	594	01	1						
563	07	7	595	55	÷						
564	07	7	596	43	RCL						
565	02	2	597	14	14						
566	85	+	598	55	÷						
567	53	(	599	43	RCL						
568	43	RCL	600	16	16						
569	25	25	601	85	+						
570	55	÷	602	43	RCL						
571	02	2	603	14	13						
572	54	)	604	54	)						
573	23	ln x	605	92	INV SBR						
574	54	)									
575	54	)									
576	24	CE									
577	44	SUM									
578	34	34									
579	53	(									

APPENDIX C

DIGITAL COMPUTER PROGRAM

```
      DIMENSION RADSKN(10),XF(10),PERMZ(10),ZF(10),ANS(2),BNDY(2)
      DIMENSION XDUM(10,25),TITLE(17),YDUM(10,25)
      COMMON/DATA/TIME(20),LWN(10),NRATE(10),BW(10),VIS(10),PERM(10),
     1THK(10),POR(10),COMP(10),SKIN(10),Q(10,15),QTIME(10,15),RADIUS(3
     20,25),RW(10),X(10),Y(10),DPENT(10)
      COMMON/VAR/DELH(25),CUMI(10,20),TSTART(10),TINS(10),VISN(10),
     1PARTHK(10),XP(25),YP(25),CAPKT,CAPHT,CAPKB,CAPHB
      COMMON/SWITCH/NT,NW,NRAD,IVIS,IMAGE,NI,ILEAK,IPENT,IFRAC
      DATA ANS/4H  NO,4H YES/
      DATA BNDY/4HSEAL,4HLEAK/
      READ(5,1300) (TITLE(I),I=1,17)
 1300 FORMAT(10X,17A4)
      READ(5,10) NT,NW,NRAD,IVIS,IMAGE,ILEAK,IDIP,IPENT,IFRAC,IREF,PI,DW
 10   FORMAT(10X,10I5,2F10.2)
      IF(ILEAK.NE.0) READ(5,20) CAPKT,CAPHT,CAPKB,CAPHB
      IF(IMAGE.NE.0) READ(5,350) ANGLE,IB1,IB2
 350  FORMAT(10X,F10.2,2I5)
      IF(IREF.EQ.0) IREF=1
      READ(5,20) (TIME(I),I=1,NT)
 20   FORMAT(10X,7F10.3)
      WRITE(6,1100)
 1100 FORMAT('1',////,T52,' DETERMINATION OF',/,T48,' AQUIFER',
     1' PRESSURE BEHAVIOR',/,T50,' UNDER FLUID INJECTION',/,T48,
     2' AND/OR PRODUCTION SYSTEMS')
      WRITE(6,1200) (TITLE(I),I=1,17)
 1200 FORMAT(//,10X,17A4,/)
      WRITE(6,900) NT,NW,NRAD
 900  FORMAT(////,T10,' INITIALIZATION DATA:',//,T15,' NT=',T22,I10,
     1T34,' NUMBER OF TIMES AT WHICH PRESSURE IS TO BE CALCULATED',/,
     2T15,' NW=',T22,I10,T34,' NUMBER OF WELLS TO BE CONSIDERED',/,
     3T15,' NRAD=',T22,I10,T34,' NUMBER OF POINTS AT WHICH PRESSURE'
     4,' IS TO BE CALCULATED')
       I1=IVIS+1
       I2=IMAGE+1
       I3=ILEAK+1
       I4=IDIP+1
       I5=IPENT+1
       I6=IFRAC+1
       IF(I6.GT.2) I6=2
       I7=IB1+1
       I8=IB2+1
      WRITE(6,910) IVIS,ANS(I1),IMAGE,ANS(I2),ILEAK,ANS(I3),IDIP,
     1ANS(I4)
 910  FORMAT(////,T10,' AQUIFER CHARACTERISTICS TO BE CONSIDERED:',
     1//,T15,' IVIS=',T22,I10,T34,' INJECTED FLUID TO HAVE VARIABLE',
     2' VISCOSITY?',A4,/,T15,' IMAGE=',T22,I10,T34,' AQUIFER CONFINED'
     3,' BY BOUNDARIES?',A4,/,T15,' ILEAK=',T22,I10,T34,' VERTICAL',
     4' AQUIFER LEAKAGE?',A4,/,T15,' IDIP=',T22,I10,T34,' DIPPING ',
     5'BED?',A4)
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      WRITE(6,920) IPENT,ANS(I5),IFRAC,ANS(I6),IREF                     00000500
  920 FORMAT(T15,' IPENT=',T22,I10,T34,' WELLS PARTIALLY PENETRA',      00000510
     1'TING BED?',A4,/,T15,' IFRAC=',T22,I10,T34,' FRACTURE ANALYSIS?'  00000520
     2,A4,/,T15,' IREF=',T22,I10,T34,' REFERENCE WELL FOR PRINTING')    00000530
      WRITE(6,930) CAPKT,CAPHT,CAPKB,CAPHB,ANGLE                        00000540
  930 FORMAT(////,T10,' GENERAL DATA CORRESPONDING TO OPTIONS SEL',     00000550
     1'ECTED:',//,T15,' CAPKT=',T23,F10.3,T34,' PERMEABILITY OF',       00000560

     2' OVERLYING BED (MD)',/,T15,' CAPHT=',T22,F10.2,T34,' THICK',     00000570
     3'NESS OF OVERLYING BED (FT)',/,T15,' CAPKB=',T23,F10.3,T34,       00000580
     4' PERMEABILITY OF UNDERLYING BED (MD)',/,T15,' CAPHB=',T22,       00000590
     5F10.2,T34,' THICKNESS OF UNDERLYING BED (FT)',/,T15,' ANGLE='     00000600
     6,T22,F10.2,T34,' ANGLE OF BOUNDARY INTERSECTION (DEG)')           00000610
      WRITE(6,940) IB1,BNDY(I7),IB2,BNDY(I8),PI,DW                      00000620
  940 FORMAT(T15,' IB1=',T22,I10,T34,' BOUNDARY 1 SEALING OR ',         00000630
     1'LEAKING?',1X,A4,/,T15,' IB2=',T22,I10,T34,' BOUNDARY',           00000640
     2' 2 SEALING OR LEAKING?',1X,A4,/,T15,' PI=',T22,F10.2,            00000650
     3T34,' INTIAL RESERVOIR PRESSURE (PSI)',/,T15,' DW=',T22,          00000660
     4F10.2,T34,' DENSITY OF RESERVOIR FLUID (LB./CU. FT.)')            00000670
      DO 30 I=1,NW                                                      00000680
      READ(5,40) LWN(I),NRATE(I),RW(I),TSTART(I),VISN(I),               00000690
     1TINS(I),RADSKN(I)                                                 00000700
   40 FORMAT(10X,2I5,6F10.0)                                            00000710
      IF(IPENT.EQ.1) READ(5,20) PARTHK(I),DPENT(I)                      00000720
      IF(LWN(I).EQ.0) LWN(I)=I                                          00000730
      IF(RADSKN(I).EQ.0.0) RADSKN(I)=100.                               00000740
      IF(IMAGE.NE.0) READ(5,20) X(I),Y(I)                               00000750
      READ(5,20) BW(I),VIS(I),PERM(I),THK(I),POR(I),COMP(I),SKIN(I)     00000760
      COMP(I)=COMP(I)*1.E-6                                             00000770
      IF(RW(I).EQ.0.0) RW(I)=3.0                                        00000780
      RW(I)=RW(I)/12.                                                   00000790
      Q(I,1)=0.0                                                        00000800
      QTIME(I,1)=0.0                                                    00000810
      NR=NRATE(I)+1                                                     00000820
      DO 70 K=2,NR                                                      00000830
      READ(5,60) Q(I,K),QTIME(I,K)                                      00000840
   60 FORMAT(10X,2F10.3)                                                00000850
   70 CONTINUE                                                          00000860
      IF(IMAGE.EQ.0.AND.IFRAC.EQ.0) READ(5,80) (RADIUS(I,K),K=1,NRAD)   00000870
   80 FORMAT(10X,7F10.3)                                                00000880
      IF(IFRAC.EQ.0) GO TO 540                                          00000890
      IF(IFRAC.NE.1) GO TO 530                                          00000900
      READ(5,80) XF(I)                                                  00000910
      DO 500 KCK=1,NRAD                                                 00000920
      READ(5,80) XV,YV                                                  00000930
      XDUM(I,KCK)=XV                                                    00000940
      YDUM(I,KCK)=YV                                                    00000950
      XXD=XV/XF(I)                                                      00000960
      YYD=YV/XF(I)                                                      00000970
      RADIUS(I,KCK)=SIGMA(XXD,YYD)                                      00000980
```

```
500   CONTINUE
      GO TO 541
530   READ(5,80) XF(I),PERMZ(I),ZF(I)
      READ(5,80) (RADIUS(I,KCK),KCK=1,NRAD)
      DO 550 KCK=1,NRAD
      RADIUS(I,KCK)=RADIUS(I,KCK)/XF(I)
550   CONTINUE
540   DO 30 K=1,NRAD
      IF (RADIUS(I,K) .LE. 0.0)  RADIUS(I,K)=RW(I)
30    CONTINUE
 541  IF (IMAGE.NE.1) GO TO 360
      DO 370 K=1,NRAD
      READ(5,80) XP(K),YP(K)
 370  CONTINUE
360   IF(IDIP.NE.0) READ(5,80) (DELH(J),J=1,NRAD)
      DO 800 I=1,NW
      WRITE(6,810) LWN(I)
810   FORMAT('1',////,T40,' RESERVOIR DESCRIPTIVE AND WELL COMPLETION'
     1,/,T48,' INPUT DATA FOR WELL',I4,//)
      WRITE(6,820) TSTART(I),PARTHK(I),PERMZ(I),RADSKN(I),PERM(I),
     1NRATE(I),VIS(I),SKIN(I),POR(I),TINS(I),THK(I),VISN(I),BW(I),
     2COMP(I),RW(I),X(I)
820   FORMAT(T15,' TSTART=',F11.2,T34,' TIME TO START OF FIRST RATE '
     1,'(DAYS)'/T15,' PARTHK=',F11.2,T34,' LENGTH OF WELL PENETRATION'
     2,' (FT)',/,T15,' PERMZ=',F12.2,T34,' VERTICAL RESERVOIR PERMEABIL'
     3,'ITY (MD)'/T15,' RADSKN=',F11.2,T34,' RADIUS EFFECTED BY SKIN'
     4,' (FT)',/,T15,' PERM=',F13.2,T34,' AREAL RESERVOIR PERMEABILITY'
     5,' (MD)'/T15,' NRATE=',I12,T34,' NUMBER OF RATES',/,T15,' VIS='
     6,F14.3,T34,' VISCOSITY OF RESERVOIR FLUID (CP)'/T15,' SKIN=',
     7F13.2,T34,' SKIN FACTOR AT WELLBORE',/,T15,' POR=',F14.3,T34,
     8' RESERVOIR POROSITY (FRACTION)'/T15,' TINS=',F13.2,T34,
     9' TIME TO START OF NEW FLUID INJECTION (DAYS)',/,T15,' THK=',
     1F14.2,T34,' RESERVOIR THICKNESS (FT)'/T15,' VISN=',F13.3,T34,
     2' NEW FLUID VISCOSITY (CP)',/,T15,' BW=',F15.2,T34,' FORMATION',
     3' VOLUME FACTOR (RB/STB)'/T15,' COMP=',F13.8,T34,' SYSTEM',
     4' COMPRESSIBILITY (1/PSI)',/,T15,' RW=',F15.3,T34,' WELLBORE',
     5' RADIUS (FT)'/T15,' X=',F16.2,T34,' REAL WELL X-LOCATION (FT)')
      WRITE(6,890) XF(I),Y(I).ZF(I).DPENT(I)
890   FORMAT(T15,' XF=',F15.3,T34,' FRACTURE LENGTH (FT)'/T15,' Y=',
     1F16.2,T34,' REAL WELL Y-LOCATION (FT)',/,T15,' ZF=',F15.3,T34,
     2' DISTANCE FROM HORIZONTAL FRACTURE',
     2/T34,' TO BOTTOM OF BED (FT)'/T15,' DPENT=',F12.2,T34,
     3' DISTANCE FROM TOP OF ZONE TO TOP OF',/,T34,
     4' PENETRATION (FT)')
      WRITE(6,830)
830   FORMAT(///,T65,' CUMULATIVE TIME',/,T41,' RATE',T51,' WELL RATE'
     1,T65,' TO END OF RATE',/,T40,' NUMBER',T51,' (STB/DAY)',T69,
     2' DAYS',/)
      KEND=NRATE(I)+1
      DO 840 K=2,KEND
      KK=K-1
      WRITE(6,850) KK,Q(I,K),QTIME(I,K)
850   FORMAT(T40,I3,T50,F10.2,T67,F10.2)
840   CONTINUE
800   CONTINUE
      IPEND=NW
      IF(IMAGE.EQ.1) IPEND=1
      DO 950 IC=1,IPEND
      IF(IMAGE.EQ.1.OR.IFRAC.EQ.1) GO TO 951
      WRITE(6,952) LWN(IC)
952   FORMAT(///,T44,' DISTANCE TO POINT X FOR WELL ',I4,/,T56,
     1' CHANGE IN',/,T43,' POINT',T56,' ELEVATION',T75,' RADIUS',
     2/,T42,' NUMBER',T58,' (FT)',T76,' (FT)',/)
      IPT=1
      IF (IFRAC .EQ. 2)  IPT=2
      GO TO 953
951   WRITE(6,954) LWN(IC)
954   FORMAT(///,T44,' DISTANCE TO POINT X FOR WELL ',I4,/,T46,
     1' CHANGE IN',/,T31,' POINT',T46,' ELEVATION',T65,' X-LOCATION'
     2,T85,' Y-LOCATION',/,T30,' NUMBER',T48,' (FT)',T69,' (FT)'
     3,T89,' (FT)',/)
      IPT=0
953   DO 960 KC=1,NRAD
      IF(IPT.EQ.1) WRITE(6,961) KC,DELH(KC),RADIUS(IC,KC)
      DUM=RADIUS(IC,KC)*XF(IC)
      IF (IPT .EQ. 2) WRITE (6,961) KC,DELH(KC),DUM
      IF(IMAGE.EQ.1) WRITE(6,962) KC,DELH(KC),XP(KC),YP(KC)
      IF(IFRAC.EQ.1) WRITE(6,962) KC,DELH(KC),XDUM(IC,KC),YDUM(IC,KC)
960   CONTINUE
961   FORMAT(T42,I6,T56,F10.2,T75,F10.2)
962   FORMAT(T30,I6,T46,F10.2,T65,F10.2,T85,F10.2)
950   CONTINUE
      IF(IVIS.NE.0) CALL VARVIS
      IF(IMAGE.NE.0) CALL DIMGE(ANGLE,IB1,IB2)
      DO 90 IT=1,NT
      WRITE(6,180) TIME(IT)
180   FORMAT(1H1,//,20X,17HPRESSURE AT TIME ,F10.3,7H (DAYS))
      IF(IFRAC.EQ.0) WRITE(6,190)
190   FORMAT(//,19X,5HPOINT,7X,11HRADIUS FROM,7X,8HPRESSURE,
     1/,18X,6HNUMBER,5X,14HREFERENCE WELL,6X,6H(PSIA),/)
      DO 100 KK=1,NRAD
      IF(IFRAC.NE.0) WRITE(6,1500) KK
1500  FORMAT(/,20X,' RADIUS POINT NUMBER=',I4,/,20X,
     1' WELL NUMBER',10X,' PRESSURE (PSIA)')
      PX=PI
      IF(IDIP.NE.0) PX=PX+(DW*DELH(KK)/144.)
      DO 110 IW=1,NW
      IF(IFRAC.EQ.0) GO TO 620
      X(IW)=PI
      PX=0.0
 620  CONTINUE
      S=SKIN(IW)
      IF(IMAGE.NE.1.AND.RADIUS(IW,KK).GT.RADSKN(IW)) S=0.0
      IF(IVIS.NE.0) S=S+CUMI(IW,IT)
      RAD=RADIUS(IW,KK)
      IEND=NRATE(IW)+1
      DO 200 ICHK=2,IEND
      LK=ICHK
      U1=QTIME(IW,ICHK)
      IF(U1.GT.TIME(IT)) GO TO 210
 200  CONTINUE
 210  TSUP=TIME(IT)-TSTART(IW)
      IF(TSUP.LE.0.0) GO TO 110
 250  DO 220 L=2,LK
      LM1=L-1
      QTERM=Q(IW,L)-Q(IW,LM1)
      TTERM=TSUP-QTIME(IW,LM1)
      QT=QTERM
      IF(IFRAC.NE.1) GO TO 510
      TDF=6.331E-3*PERM(IW)*TTERM/(POR(IW)*VIS(IW)*COMP(IW)*XF(IW)**2)
      IF(RADIUS(IW,KK).EQ.1.E20) GO TO 591
      PD=.5*(ALOG(TDF)+2.80907)+RADIUS(IW,KK)
      GO TO 240
 510  IF(IFRAC.NE.2) GO TO 520
      TDF=6.331E-3*PERM(IW)*TTERM/(POR(IW)*COMP(IW)*VIS(IW)*XF(IW)**2)
      HD=THK(IW)*SQRT(PERM(IW)/PERMZ(IW))/XF(IW)
      TC1=12.5*(2.*RADIUS(IW,KK)**2+1.)
      TC2=5.*HD**2/(3.14159**2)
      IF(TDF.LT.TC1.OR.TDF.LT.TC2) GO TO 560
      RD2=RADIUS(IW,KK)**2
      PD=.5*(ALOG(TDF)+1.80907-RD2)
      IF(RADIUS(IW,KK).GT.1.) PD=.5*(ALOG(TDF/RD2)+.80907)
      RTST=XF(IW)+10.*THK(IW)*SQRT(PERM(IW)/PERMZ(IW))/3.14159
      R=RADIUS(IW,KK)*XF(IW)
      IF(R.LT.RTST.AND.R.NE.0.0) GO TO 570
      SGM=0.0
      ZFH=ZF(IW)/THK(IW)
      IF(R.EQ.0.0) SGM=SIGHOR(HD,ZFH)
      PD=PD+SGM
      GO TO 240
 560  WRITE(6,580) IW,TIME(IT)
 580  FORMAT(/,' APPROXIMATIONS FOR HORIZONTAL FRCTURE FAIL DUE',
     1' TO TD LIMITATIONS FOR WELL ',I4,' TIME=',F10.2)
      GO TO 590
 570  WRITE(6,600) IW,R
 600  FORMAT(/,' APPROXIMATIONS FOR HORIZONTAL FRACTURE FAIL DUE TO',
     1' RADIUS LIMITATIONS FOR WELL ',I4,' RADIUS=',F10.2)
      GO TO 590
```

```
591   WRITE(6,592) IW,KK
592   FORMAT(/,' APPROXIMATION FOR VERTICAL FRACTURE PSUEDO',
     1' SKIN FAIL FOR WELL',I4,' RADIUS NO.',I4)
590   CONTINUE
520   CONTINUE
      IF(IMAGE.NE.1) GO TO 300
      IS=NI*(IW-1)
      DO 220 IK=1,NI
      KSUB=IK+IS
      IF(IW.EQ.IREF.AND.IK.EQ.1) KPRNT=KSUB
      IF(IK.EQ.1.AND.ABS(RADIUS(KSUB,KK)).GT.RADSKN(IW))
     1S=S-SKIN(IW)
      ISIGN=1
      IF(RADIUS(KSUB,KK).LT.0.0) ISIGN=-1
      RAD=ABS(RADIUS(KSUB,KK))
      QT=QT*ISIGN
300   CALL PRESS(IW,RAD,TTERM,PD,S,&240)
      PX=PX+(70.6*QT*VIS(IW)*BW(IW)*PD/(PERM(IW)*THK(IW)))
      GO TO 220
240   PX=PX+(PD*QT*VIS(IW)*BW(IW)/(7.082E-3*PERM(IW)*THK(IW)))
220   CONTINUE
      IF(IFRAC.NE.0) X(IW)=X(IW)+PX
      IF(IFRAC.NE.0) WRITE(6,1600) IW,X(IW)
1600  FORMAT(20X,I10,11X,F11.2)
110   CONTINUE
       IF(IMAGE.NE.1) KPRNT=IREF
      IF(IFRAC.EQ.0) WRITE(6,390) KK,RADIUS(KPRNT,KK),PX
390   FORMAT(17X,I4,7X,F15.3,3X,F10.3)
100   CONTINUE
90    CONTINUE
      STOP
      END
      FUNCTION EI(ZZ)
      REAL*8 FAC,U,Y,RI,DC
      DIMENSION K(10)
      DATA K/6,8,10,16,18,20,24,28,32,34/
      Z=ABS(ZZ)
      FI=0.0
      IF(Z.GT.10.) RETURN
      C=.5772
      U=DBLE(Z)
      DC=DBLE(C)
      Y=-DC-DLOG(U)
      FAC=1.D0
      IZ=Z
      IF(IZ.GT.9) IZ=9
      KC=K(IZ+1)
      IF(Z.LT.1.E-10) KC=3
      DO 10 I=1,KC
      RI=DFLOAT(I)
      FAC=FAC*(-RI)
      Y=Y-(U**I)/(RI*FAC)
10    CONTINUE
      IF(Y.LT.0.0) Y=0.0
      T=SNGL(Y)
      EI=T
      RETURN
      END
      SUBROUTINE PRESS(IWN,RAD,T,PF,SKN,*)
      COMMON/DATA/TIME(20),LWN(10),NRATE(10),BW(10),VIS(10),PERM(10),
     1THK(10),POR(10),COMP(10),SKIN(10),Q(10,15),QTIME(10,15),RADIUS(3
     20,25),RW(10),X(10),Y(10),DPENT(10)
      COMMON/VAR/DELH(25),CUMI(10,20),TSTART(10),TINS(10),VISN(10),
     1PARTHK(10),XP(25),YP(25),CAPKT,CAPHT,CAPKB,CAPHB
      COMMON/SWITCH/NT,NW,NRAD,IVIS,IMAGE,NI,ILEAK,IPENT,IFRAC
      IKEY=0
      IF (T .EQ. 0.0)  T=1.E-5
      IF(ILEAK.NE.1) GO TO 10
      TU=0.0
      TL=0.0
      IF(CAPHT.NE.0.0) TU=CAPKT/(PERM(IWN)*THK(IWN)*CAPHT)
      IF(CAPHB.NE.0.0) TL=CAPKB/(PERM(IWN)*THK(IWN)*CAPHB)
      TSUM=TU+TL
      B=1.0/SQRT(TSUM)
      U=POR(IWN)*VIS(IWN)*COMP(IWN)*RAD**2/(2.532E-2*PERM(IWN)*T)
      RBB=RAD/B
      RB2=RBB**2/(4.*U)
      RB=BESSEL(RBB)
      IF(U.LE.1.0) GO TO 100
      T1=.5772+ALOG(RB2)+EI(RB2)-RB2+((RB-1.)/U)
      T1=EXP(-U)*T1
      DUM=RB*EI(U)-T1
      GO TO 150
100   DUM=RB*EI(RB2)
      T1=-(ALOG(RBB/2.)+.5772)*RB+(RBB**2/4.)+.0234375
     1*(RBB**4)
      DUM=2.*T1-DUM
      T2=U*(RB-1.)/((RBB**2)/4.)
      T2=.5772+ALOG(U)+EI(U)-U+T2
150   SUMN=0.0
      DO 3 N=1,6
      SUMM=0.0
      DO 2 M=1,N
      NM1=N-M+1
      F1=1.
      DO 5 I=1,NM1
5     F1=F1*FLOAT(I)
      N2=N+2
      F2=1.
      DO 4 I=1,N2
4     F2=F2*FLOAT(I)
      IF(U.LE.1.0) GO TO 120
      SUMM=SUMM+((-1.)**(N+M))*F1*(((RBB**2)/4.)**N)/
     1((F2**2)*(U**(N-M)))
      GO TO 2
120   SUMM=SUMM+((-1.)**(N+M))*F1*(((RBB**2)/4.)**M)*(U**(N-M))
     1/(F2**2)
2     CONTINUE
3     SUMN=SUMN+SUMM
      IF(U.LE.1.0) GO TO 130
      TER=0.0
      IF(U.LT.174.) TER=EXP(-U)
      SUMN=SUMN*TER/(U**2)
      PR=(SUMN+DUM)/2.+(2.*SKN)
      GO TO 500
130   SUMN=SUMN*(U**2)
      TER=0.0
      IF(RB2.LT.174.) TER=EXP(-RB2)
      T3=DUM+TER*(T2-SUMN)
      PR=T3/2.+(2.*SKN)
500   CONTINUE
      IF(IPENT.NE.1) RETURN 1
      IKEY=1
10    RTEST=1.5*THK(IWN)
      IF(IPENT.NE.1.OR.RAD.GT.RTEST) GO TO 20
      U=POR(IWN)*VIS(IWN)*COMP(IWN)*RAD**2/(2.532E-2*PERM(IWN)*T)
      IF(IKEY.EQ.1) GO TO 30
      PR=PARPEN(U,RAD,THK(IWN),PARTHK(IWN),DPENT(IWN),IKEY)
      RETURN 1
30    PR=PR+PARPEN(U,RAD,THK(IWN),PARTHK(IWN),DPENT(IWN),IKEY)
      RETURN 1
20    IF(IKEY.EQ.1) RETURN 1
      TERM=39.51*POR(IWN)*VIS(IWN)*COMP(IWN)*RAD**2/(PERM(IWN)*T)
      PR=EI(TERM)+2.*SKN
      RETURN
      END
      SUBROUTINE DIMGE(THETA,IBOND1,IBOND2)
      COMMON/DATA/TIME(20),LWN(10),NRATE(10),BW(10),VIS(10),PERM(10),
     1THK(10),POR(10),COMP(10),SKIN(10),Q(10,15),QTIME(10,15),RADIUS(3
     20,25),RW(10),X(10),Y(10),DPENT(10)
      COMMON/VAR/DELH(25),CUMI(10,20),TSTART(10),TINS(10),VISN(10),
     1PARTHK(10),XP(25),YP(25),CAPKT,CAPHT,CAPKB,CAPHB
      COMMON/SWITCH/NT,NW,NRAD,IVIS,IMAGE,NI,ILEAK,IPENT,IFRAC
      DIMENSION XI(10,30),YI(10,30)
      IKZB=0
      IF(THETA.EQ.360.) GO TO 50
      NI=360./THETA
      IEND=NI-1
      TANG=TAN((THETA/57.29578))                                        00003930
      SLPE=-1.0/TANG                                                    00003940
      A=1.0+SLPE**2                                                     00003950
      DO 10 IW=1,NW                                                     00003960
      R2=X(IW)**2+Y(IW)**2                                              00003970
      XI(IW,1)=X(IW)                                                    00003980
      YI(IW,1)=Y(IW)                                                    00003990
      XI(IW,2)=X(IW)                                                    00004000
      YI(IW,2)=-Y(IW)                                                   00004010
      IF(NI.LE.2) GO TO 10                                              00004020
      DO 10 IM=3,IEND                                                   00004030
      IM1=IM-1                                                          00004040
      IP1=IM+1                                                          00004050
      B=2.*(SLPE*YI(IW,IM1)-XI(IW,IM1)*SLPE**2)                         00004060
      C=XI(IW,IM1)**2*SLPE**2-2.*SLPE*XI(IW,IM1)*YI(IW,IM1)             00004070
      C=C+YI(IW,IM1)**2-R2                                              00004080
      DISC=B**2-4.*A*C                                                  00004090
      DISC=SQRT(DISC)                                                   00004100
      XI(IW,IM)=(-B-DISC)/(2.*A)                                        00004110
      DIFF=XI(IW,IM)-XI(IW,IM1)                                         00004120
      DIFF=ABS(DIFF)                                                    00004130
      IF(DIFF.LE..001) XI(IW,IM)=(-B+DISC)/(2.*A)                       00004140
      YI(IW,IM)=SLPE*(XI(IW,IM)-XI(IW,IM1))+YI(IW,IM1)                  00004150
      XI(IW,IP1)=XI(IW,IM)                                              00004160
      YI(IW,IP1)=-YI(IW,IM)                                             00004170
10    CONTINUE                                                          00004180
      DO 20 I=1,NW                                                      00004190
      IS=NI*(I-1)                                                       00004200
      DO 20 K=1,NI                                                      00004210
      KSUB=K+IS                                                         00004220
      ISIGN=1                                                           00004230
      IF(K.EQ.1) GO  TO 40                                              00004240
      IF(IKZB.EQ.1) GO TO 100                                           00004250
      IF(IBOND1.EQ.1.AND.YI(IW,K).LT.0.0) ISIGN=-1                      00004260
      IF(IBOND2.NE.1) GO TO 40                                          00004270
      YTEST=TANG*XI(IW,K)                                               00004280
      IF(YTEST.LT.YI(IW,K)) ISIGN=-1                                    00004290
      GO TO 40                                                          00004300
100   IF(IBOND1.EQ.1.AND.K.GE.5) ISIGN=-1                               00004310
      IF(IBOND2.EQ.1.AND.K.LE.4) ISIGN=-1                               00004320
40    CONTINUE                                                          00004330
      DO 20 J=1,NRAD                                                    00004340
      RDUM=(XP(J)-XI(IW,K))**2+(YP(J)-YI(IW,K))**2                      00004350
      RADIUS(KSUB,J)=SQRT(RDUM)*ISIGN                                   00004360
      IF (RADIUS(KSUB,J).EQ.0.0)  RADIUS(KSUB,J)=RW(I)                  00004370
20    CONTINUE                                                          00004380
      RETURN                                                            00004390
50    CONTINUE                                                          00004400
      XL=X(1)                                                           00004410
      XR=Y(1)                                                       00004420
      X(1)=0.0                                                      00004430
      Y(1)=0.0                                                      00004440
      XI(1,1)=0.0                                                   00004450
      YI(1,1)=0.0                                                   00004460
      DO 60 IW=1,NW                                                 00004470
      IF(IW.EQ.1) GO TO 70                                          00004480
      XI(IW,1)=X(IW)                                                00004490
      YI(IW,1)=Y(IW)                                                00004500
70    ADL=XL-X(IW)                                                  00004510
      ADR=XR-X(IW)                                                  00004520
      XI(IW,2)=XR+ADR                                               00004530
      XI(IW,3)=XI(IW,2)+2.*ABS(ADL)                                 00004540
      XI(IW,4)=XI(IW,3)+2.*ADR                                      00004550
      XI(IW,5)=XL-ABS(ADL)                                          00004560
      XI(IW,6)=XI(IW,5)-2.*ABS(ADR)                                 00004570
      XI(IW,7)=XI(IW,6)-2.*ABS(ADL)                                 00004580
      DC 60 K=2,7                                                   00004590
      YI(IW,K)=Y(IW)                                                00004600
60    CONTINUE                                                      00004610
      NI=7                                                          00004620
      IKZB=1                                                        00004630
      GO TO 10                                                      00004640
110   RETURN                                                        00004650
      END                                                           00004660
      SUBROUTINE VARVIS                                             00004670
      COMMON/DATA/TIME(20),LWN(10),NRATE(10),BW(10),VIS(10),PERM(10),    00004680
     1THK(10),POR(10),COMP(10),SKIN(10),Q(10,15),QTIME(10,15),RADIUS(3   00004690
     20,25),RW(10),X(10),Y(10),DPENT(10)                            00004700
      COMMON/VAR/DELH(25),CUMI(10,20),TSTART(10),TINS(10),VISN(10), 00004710
     1PARTHK(10),XP(25),YP(25),CAPKT,CAPHT,CAPKB,CAPHB              00004720
      COMMON/SWITCH/NT,NW,NRAD,IVIS,IMAGE,NI,ILEAK,IPENT,IFRAC      00004730
      DC 20 IW=1,NW                                                 00004740
      DO 20 IT=1,NT                                                 00004750
      IKEY=0                                                        00004760
      CUMI(IW,IT)=0.0                                               00004770
      IF(VISN(IW).EQ.0.0.OR.TINS(IW).GE.TIME(IT)) GO TO 20          00004780
       ISTOP=NRATE(IW)+1                                            00004790
      DO 30 I=2,ISTOP                                               00004800
      T=QTIME(IW,I)                                                 00004810
      IF(IKEY.NE.0) GO TO 10                                        00004820
      IF(TINS(IW).GT.QTIME(IW,I)) GO TO 30                          00004830
      TS=TINS(IW)                                                   00004840
      IKEY=1                                                        00004850
      GO TO 50                                                      00004860
10    TS=QTIME(IW,I-1)                                              00004870
50    IF(TIME(IT).LT.QTIME(IW,I)) T=TIME(IT)                        00004880
      TR=T-TS                                                       00004890
      CUMI(IW,IT)=CUMI(IW,IT)+TR*Q(IW,I)                            00004900
      IF(T.EQ.TIME(IT)) GO TO 20
   30 CONTINUE
   20 CONTINUE
      DO 60 IW=1,NW
      IF(VISN(IW).EQ.0.0) GO TO 60
       FAC=5.615*BW(IW)/(3.1416*THK(IW)*POR(IW))
      RF=RW(IW)**2
      PERMN=PERM(IW)*VIS(IW)/VISN(IW)
      DO 60 IT=1,NT
      R=FAC*CUMI(IW,IT)+RF
       CUMI(IW,IT)=SQRT(R)
      RTERM=ALOG((CUMI(IW,IT)/RW(IW)))
      CUMI(IW,IT)=(PERM(IW)/PERMN-1.0)*RTERM
   60 CONTINUE
      RETURN
      END
      FUNCTION BESSEL(X)
      REAL*8 XX,RI,SUM,FAC
      XX=DBLE(X)
      XX=XX**2/4.D0
      FAC=1.D0
      SUM=1.D0
      DO 10 I=1,6
      RI=DFLOAT(I)
      FAC=FAC*RI
      SUM=SUM+(XX**I/FAC**2)
   10 CONTINUE
      BESSEL=SNGL(SUM)
      RETURN
      END
      FUNCTION PARPEN(UD,RD,HD,RLD,DD,IKEY)
      IMPLICIT REAL*8(A-H,O-Z)
      REAL PARPEN,UD,RD,HD,RLD,DD,BESSEL
      U=DBLE(UD)
      R=DBLE(RD)
      H=DBLE(HD)
      RL=DBLE(RLD)
      D=DBLE(DD)
      PI=3.141592654
      Y=0.0
      IF(IKEY.NE.1) CALL DEI(U,Y)
      TSCH=2.*H**2*U/(R**2)
      IF(TSCH.LT.1.) GO TO 10
      SUM=0.0
      DO 2 I=1,100
      RI=DFLOAT(I)
      C=(RI*PI*R/(2.*H))**2
      CALL ROM(U,C,Q)
    2 SUM=SUM+Q*DSIN(RI*PI*RL/H)/RI
```

```
      SUM=SUM*2.*H/PI/RL
      Z=(SUM+Y)/2.
      PARPEN=SNGL(Z)
      RETURN
10    SUM=0.0
      DO 20 I=1,100
      RI=DFLOAT(I)
      AUG=PI*RI/H
      A=DSIN(AUG*RL)
      B=DSIN(AUG*D)
      C=DCOS(AUG*D)
      DDD=AUG*R
      BSL=DBLE(BESSEL(DD))
      E=-(DLOG(DDD/2.)+.5772)*BSL+(DDD**2/4.)+.0234375*(DDD**4)
      SUM=SUM+(E*(A-B)*C/RI)
20    CONTINUE
      SUM=SUM*4.*H/(PI*(RL-D))
      Z=(SUM+Y)/2.
      PARPEN=SNGL(Z)
      RETURN
      END
      SUBROUTINE ROM(A,C,Q)
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION T(50)
      B=100.*A
      IF(A.LT.1.0) B=B*100.
      EPS=0.0000000005
      DEL=.05
      XO=A
      H=B-A
      T(1)=(H/2.)*(FCT(A,C)+FCT(B,C))
      N=1
    5 H=H/2.
      S=FCT(A,C)
      LIM=2**N-1
      DO 10 J=1,LIM
      X=XO+DFLOAT(J)*H
   10 S=S+2.0*FCT(X,C)
      T(N+1)=(H/2.)*(S+FCT(B,C))
      IF (DABS(T(N+1)-T(N))-EPS) 60,60,15
   15 IF (H-DEL) 25,25,20
   20 N=N+1
   22 GO TO 5
   25 NMAX=N
      N=1
   26 M=1
      K=N
   28 T(K)=(4.**M*T(K+1)-T(K))/(4.**M-1.)
      IF (K-1) 40,40,30
```

```
 30 IF (DABS(T(K)-T(K-1))-EPS) 50,50,35                          00005890
 35 M=M+1                                                        00005900
    K=K-1                                                        00005910
    GO TO 28                                                     00005920
 40 N=N+1                                                        00005930
    IF (N-NMAX) 26,26,45                                         00005940
 45 DEL=DEL/2.                                                   00005950
    GO TO 5                                                      00005960
 50 CONTINUE                                                     00005970
    Q=T(K)                                                       00005980
    GO TO 65                                                     00005990
 60 CONTINUE                                                     00006000
    Q=T(N+1)                                                     00006010
 65 RETURN                                                       00006020
    END                                                          00006030
    SUBROUTINE DEI(U,Y)                                          00006040
    IMPLICIT REAL*8(A-H,O-Z)                                     00006050
    DIMENSION K(10)                                              00006060
    DATA K/6,8,10,16,18,20,24,28,32,34/                          00006070
    U=DABS(U)                                                    00006080
    Y=0.0                                                        00006090
    IF(U.GT.10.) RETURN                                          00006100
    DC=.5772                                                     00006110
    Y=-DC-DLOG(U)                                                00006120
    FAC=1.D0                                                     00006130
    IZ=U                                                         00006140
    IF(IZ.GT.9) IZ=9                                             00006150
    KC=K(IZ+1)                                                   00006160
    IF(U.LT.1.D-10) KC=3                                         00006170
    DO 10 I=1,KC                                                 00006180
    RI=DFLOAT(I)                                                 00006190
    FAC=FAC*(-RI)                                                00006200
    Y=Y-(U**I)/(RI*FAC)                                          00006210
 10 CONTINUE                                                     00006220
    IF(Y.LT.0.0) Y=0.0                                           00006230
    RETURN                                                       00006240
    END                                                          00006250
    FUNCTION FCT(A,C)                                            00006260
    IMPLICIT REAL*8(A-H,O-Z)                                     00006270
    FCT=0.0                                                      00006280
    AUG=-A-C/A                                                   00006290
    IF(AUG.LT.-170.) RETURN                                      00006300
    FCT=(DEXP(AUG))/A                                            00006310
    RETURN                                                       00006320
    END                                                          00006330
    FUNCTION SIGMA(XD,YD)                                        00006340
    XM1=XD-1.0                                                   00006350
    XP1=XD+1.0                                                   00006360
    RD2=XD**2+YD**2                                              00006370
```

```
      IF(XM1.EQ.0..AND.YD.EQ.0..OR.XP1.EQ.0..AND.YD.EQ.0.) GO TO 10    00006380
      A=XM1*ALOG(YD**2+XM1**2)                                          00006390
      B=XP1*ALOG(YD**2+XP1**2)                                          00006400
      DEM=RD2-1.0                                                       00006410
      IF(DEM.EQ.0.0) GO TO 10                                           00006420
      RATIO=2.*YD/DEM                                                   00006430
      C=2.*YD*ATAN(RATIO)                                               00006440
      IF(C.LT.0.0) C=0.0                                                00006450
      SIGMA=(A-B-C)/4.                                                  00006460
      RETURN                                                            00006470
   10 SIGMA=1.E20                                                       00006480
      RETURN                                                            00006490
      END                                                               00006500
      FUNCTION SIGHOR(H,Z)                                              00006510
      IMPLICIT REAL*8 (A-H,O-Z)                                         00006520
      REAL*4 H,Z,SIGHOR                                                 00006530
      PI=3.141592654                                                    00006540
      HD=DBLE(H)                                                        00006550
      ZFH=CBLE(Z)                                                       00006560
      A=1.-(3.*ZFH*(1.-ZFH))                                            00006570
      A=2.*A*HD**2/3.                                                   00006580
      SIGHOR=SNGL(A)                                                    00006590
      IF(HD.LT.1.0) RETURN                                              00006600
      SUM=0.0                                                           00006610
      DO 20 I=1,20                                                      00006620
      RI=DFLOAT(I)                                                      00006630
      AUG=RI*PI*ZFH                                                     00006640
      B=(DCOS(AUG))**2/RI                                               00006650
      T=RI*PI/HD                                                        00006660
      BES=1./T                                                          00006670
      IF (T.GT.5.) BES=DSQRT(PI/(2.*T))*(1.+(3./(8.*T)))*DEXP(-T)       00006680
      B=B*BES                                                           00006690
   20 SUM=SUM+B                                                         00006700
      SUM=SUM*4.*HD/PI                                                  00006710
      SIGHOR=SNGL(A-SUM)                                                00006720
      RETURN                                                            00006730
      END                                                               00006740
```

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